The Earth's Shape and Map Projections

Modeling a Lumpy Space Potato

Intro to GIS – UMass Amherst – Michael F. Nelson

Upcoming Important Dates!

- Labs 0, 1, and 2 due **tomorrow** (July 16th by 11:59PM)
- Labs 3 and 4 due **next Friday July 23**
  - Previously due on Monday the 19th.
  - These labs are more technical – don't wait to start them!
- Final Project Sign-Up due **next Friday July 23**
- Midterm begins the week of **July 26 (week after next)**
  - Check out the study materials (link on GitHub page)
  - Focus on the technical differences between Selections and Geoprocessing operations
  - Think about when to use select vs. geoprocessing

Announcements

- Map forum is now on Moodle.
- All videos are now on Echo360
  - You should at least check out the course page so that you know how to access it if you need to!
- Reach out with questions!
- Come to labs, even if it is only for a quick drop-in.

Overview

Finish Vector Analysis Slides

The Earth’s Shape

- Models
  - Spheres, geoids, and ellipsoids
- Datums and Coordinate Systems

Projections and Maps

- Types of Projections
- Map Classes

Stop and re-start Zoom Recording

Note to self!

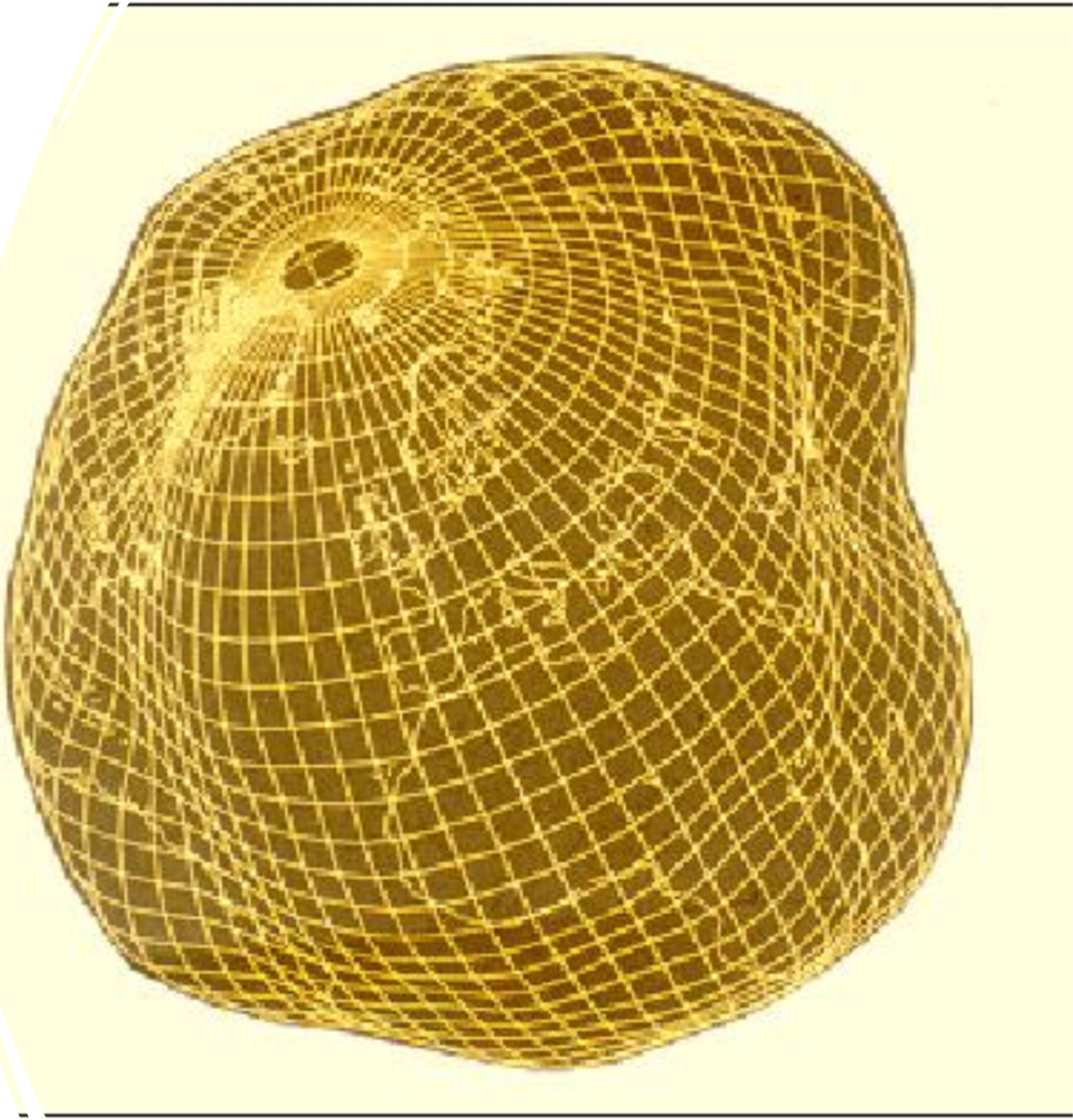
Stop and re-start Zoom Recording

Note to self!

What is the shape of the Earth?

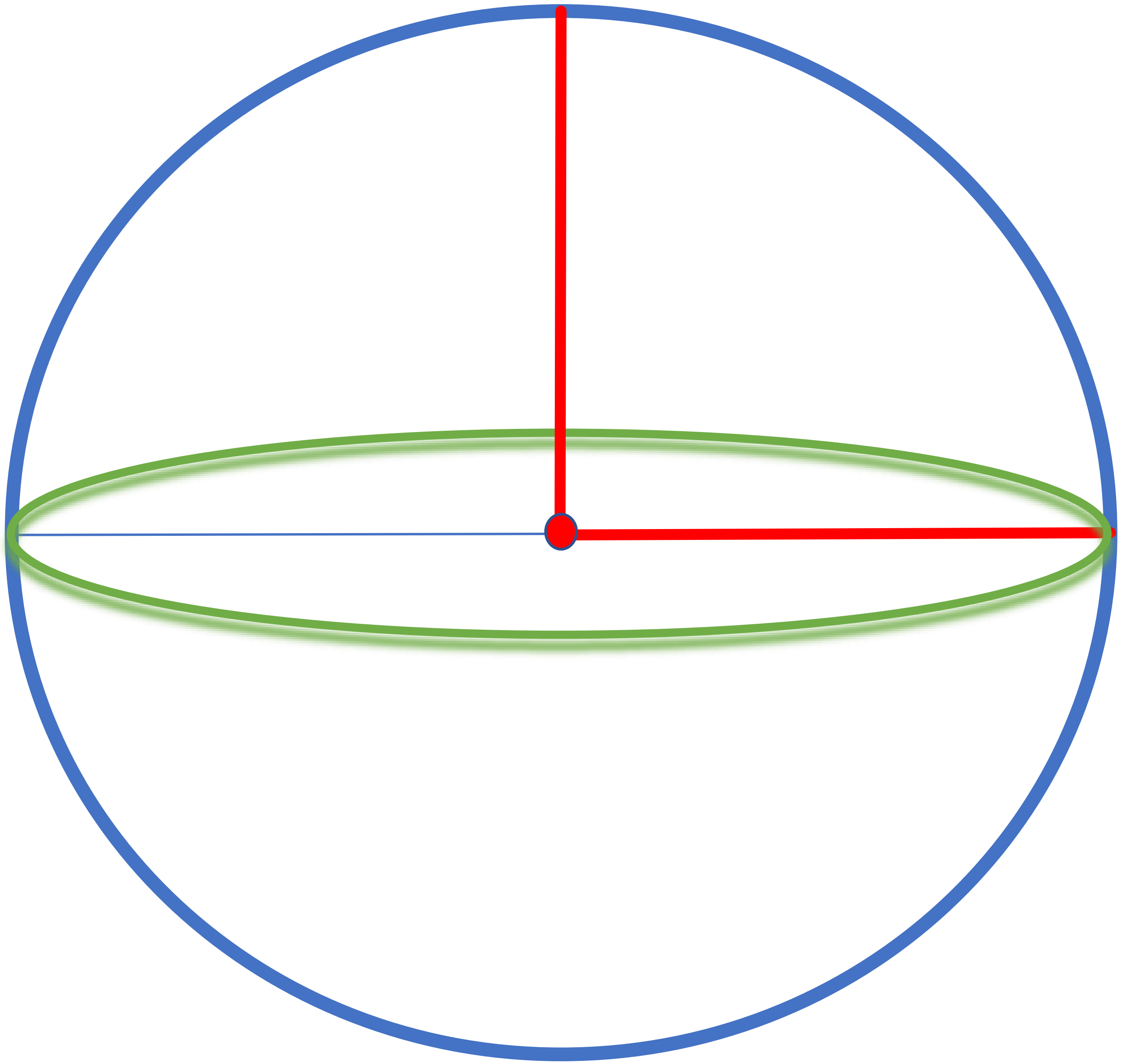
Model Thinking and ‘Reality’

What is Earth’s shape?

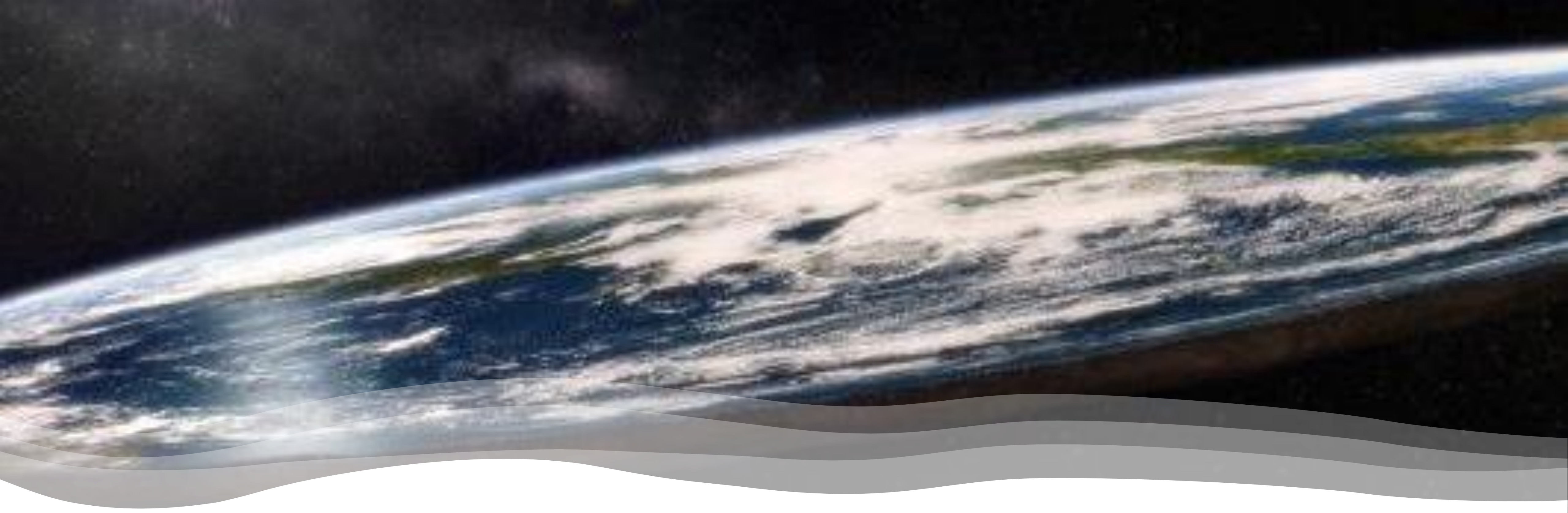


Model Thinking: A useful simplification of the earth's shape?

- Flat*?
- Sphere?
- Ellipsoid?
- Lumpy Space Potato?
- Geoid?



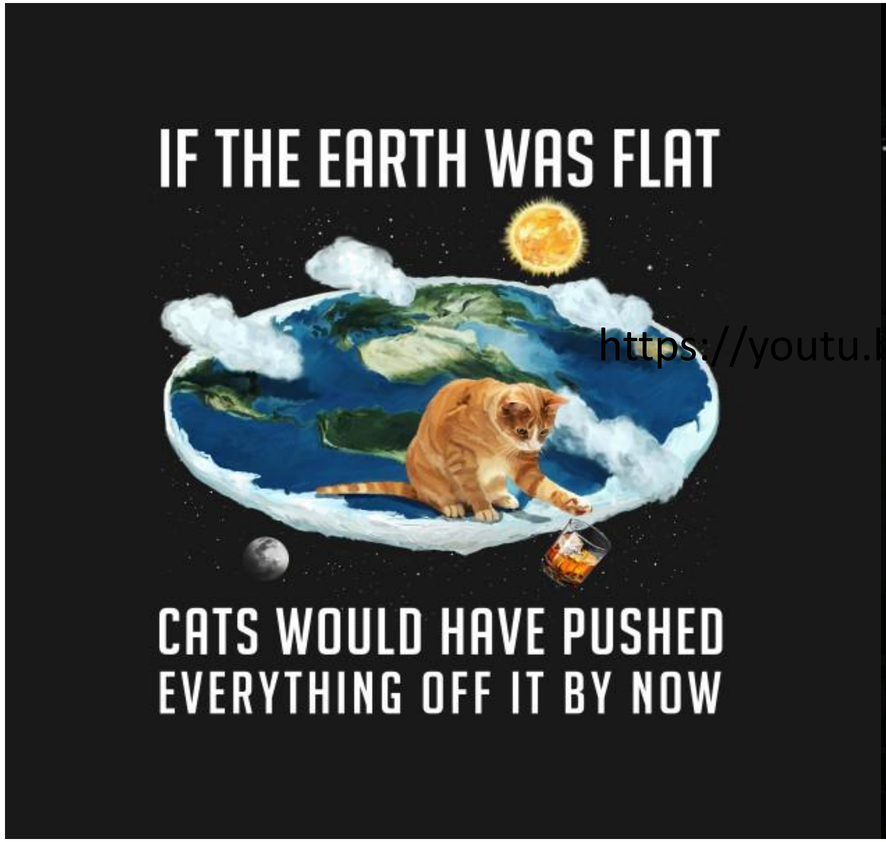
* The earth is not flat.



If Earth were flat, GIS would be way easier

Projections & Coordinate systems

If the Earth were Flat…



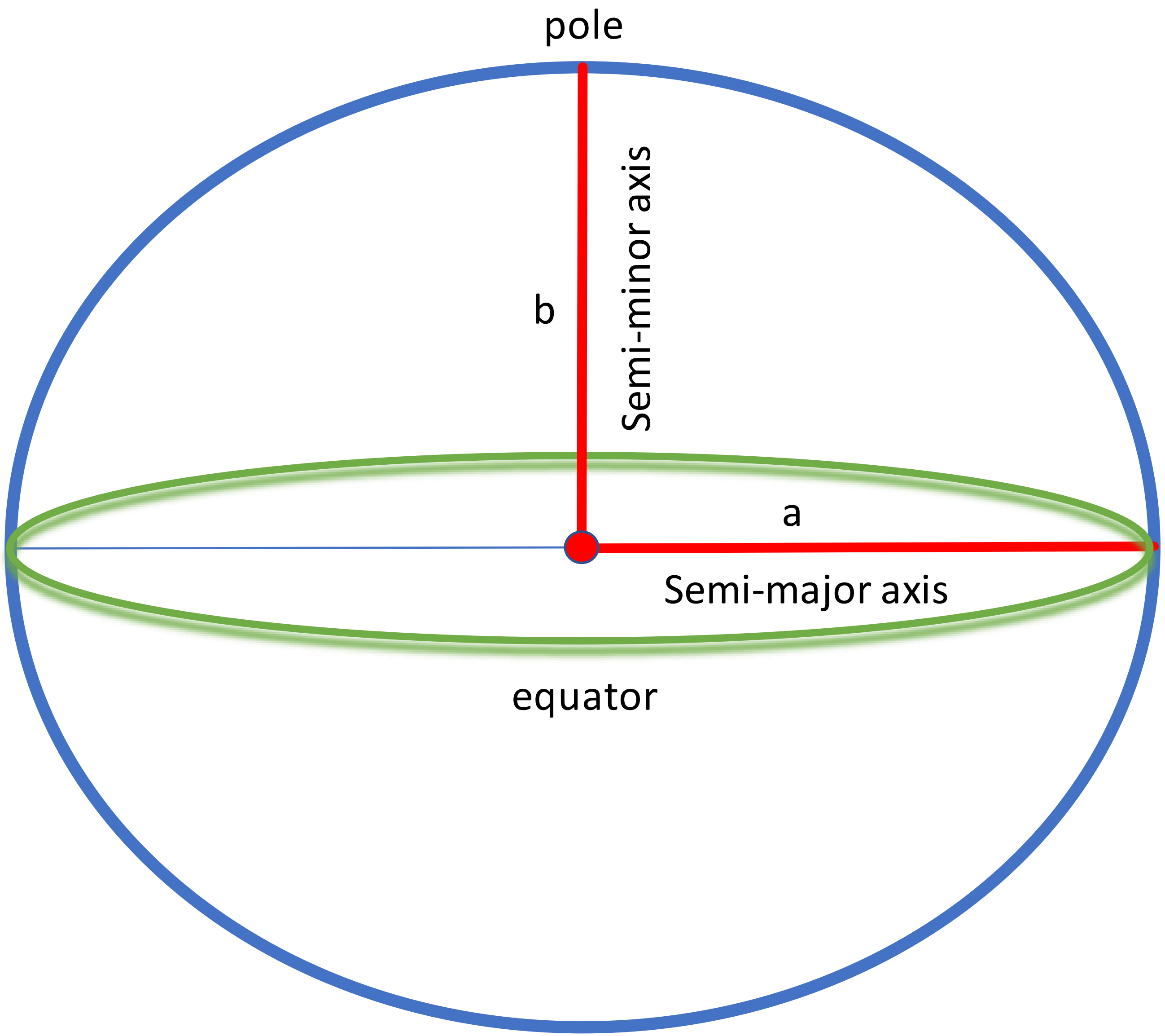
https://youtu.be/e09AxnrkiXk

Just ask Gato Malo

Spherical Model

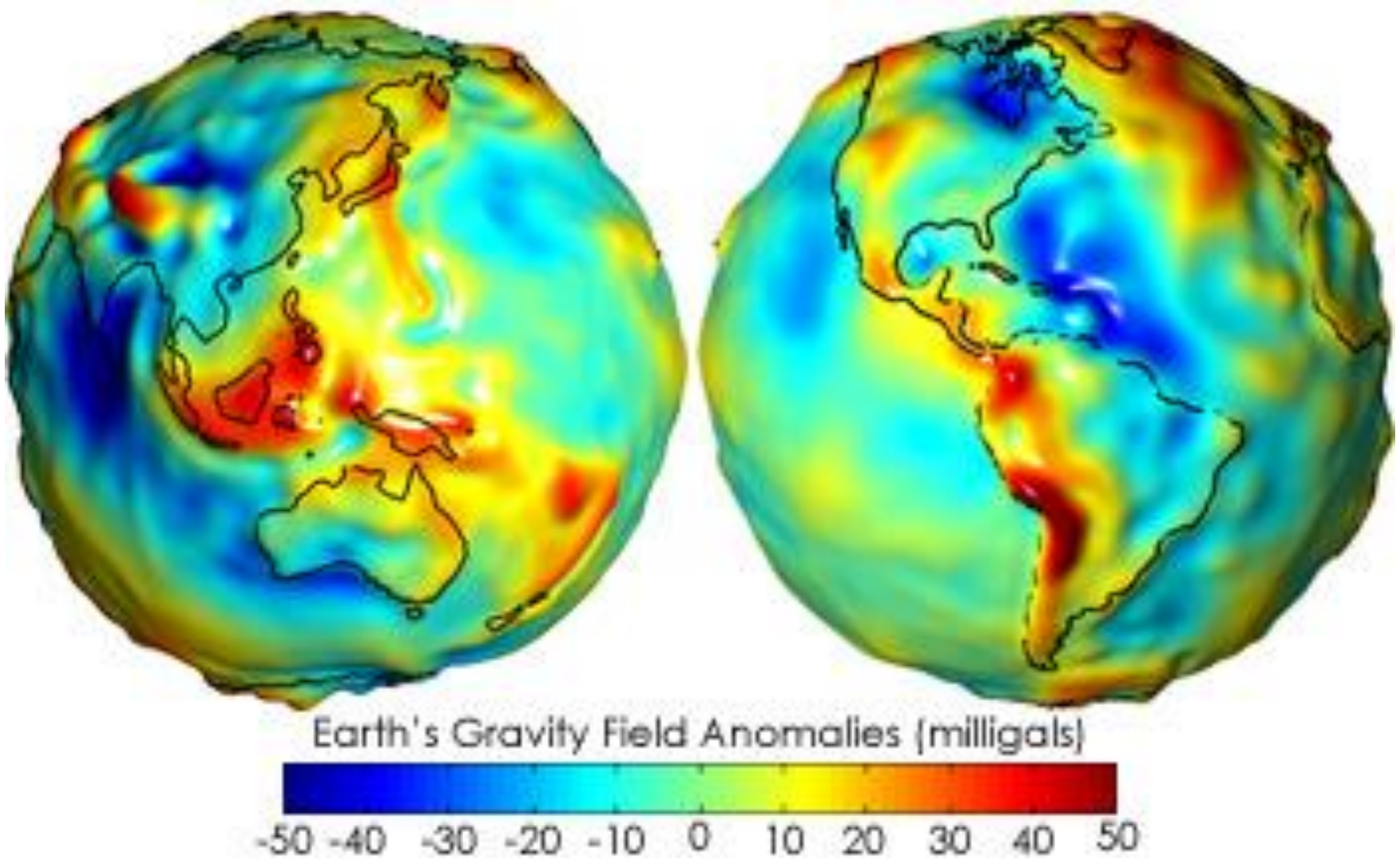
Ellipsoid Models

- $A\ measure\ of\ flattening$:
- $f = \frac{a-b}{a}$



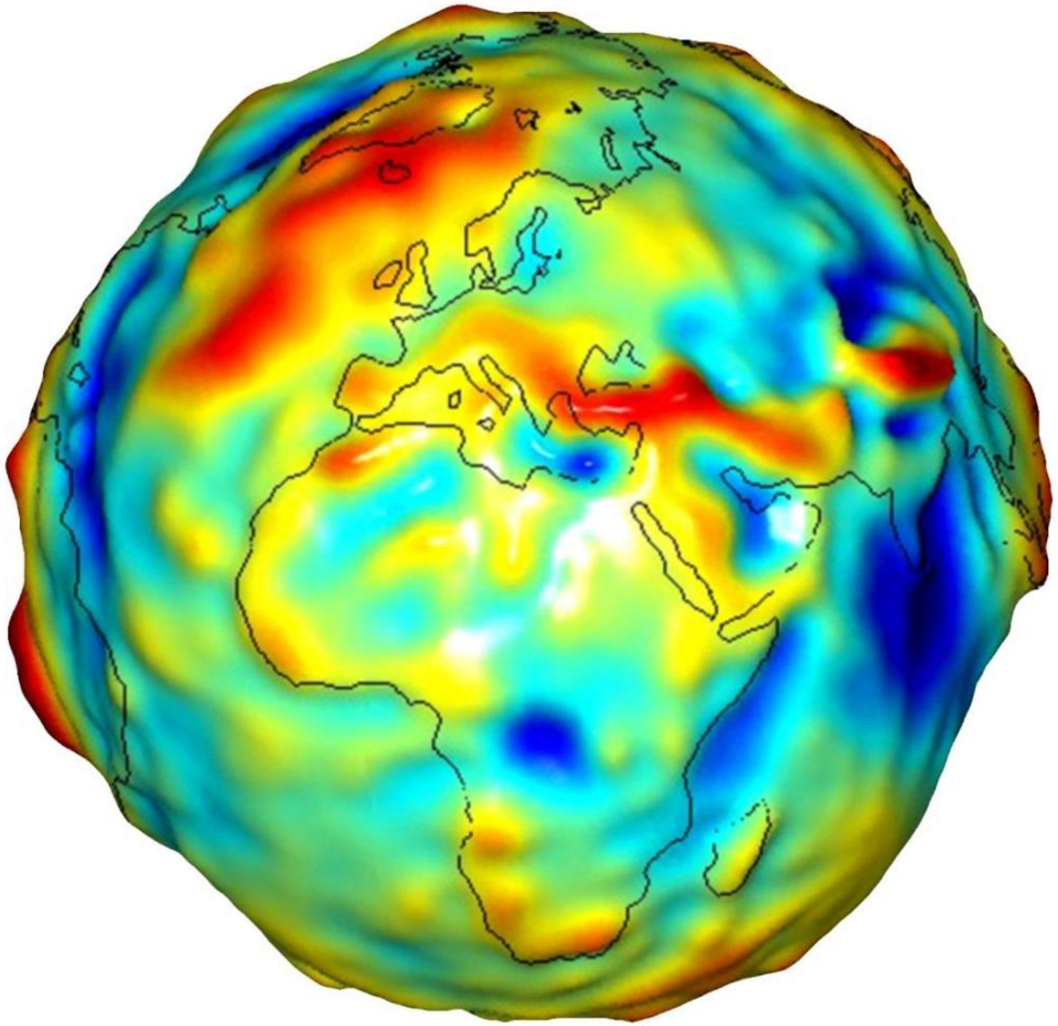
A lumpy space potato?

Earth is NOT a perfect ellipsoid or a sphere



Lumpy Space Potato

- The true shape of the earth is more like a lumpy potato with undulations from the ellipsoid as much as 100 m.
- There is also a large bulge in the earth of 10 to 15m in the Southern Hemisphere giving rise to the description of earth as **pear shaped.**

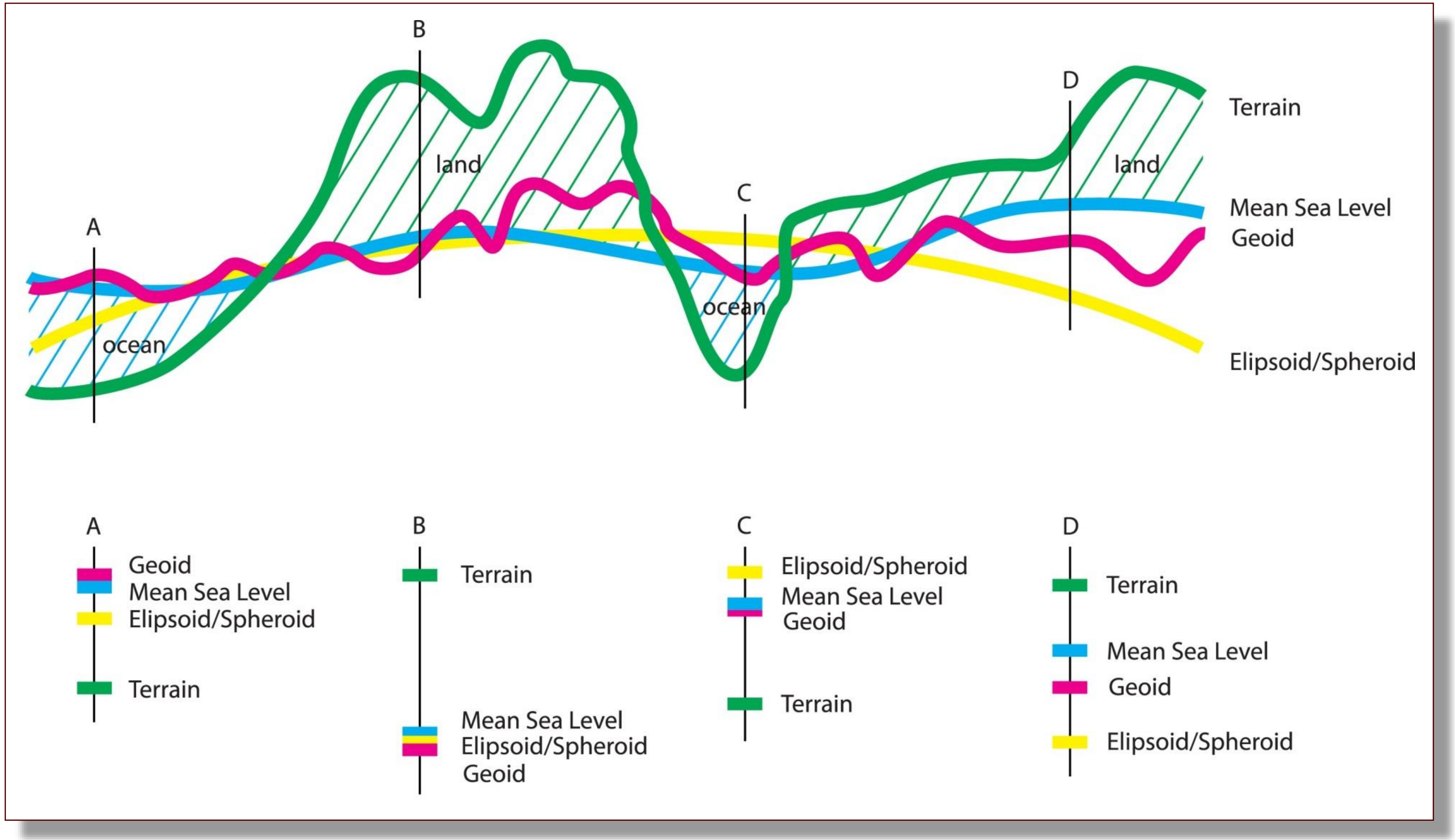


Source: Paul Bolstad. 2012. GIS Fundamentals – A first text on Geographic Information Systems. 4th ed.

What is Earth's true shape?

- The actual shape of the Earth is a Geoid, literally "Earth Shaped".
- The Geoid is determined by gravitational measurements.
- The Geoid is similar to the Earth's **mean-sea-level** surface.
    - For land, MSL is height to which water would rise in a well that is connected to the ocean.

Terrain, Ellipsoid, and Geoid



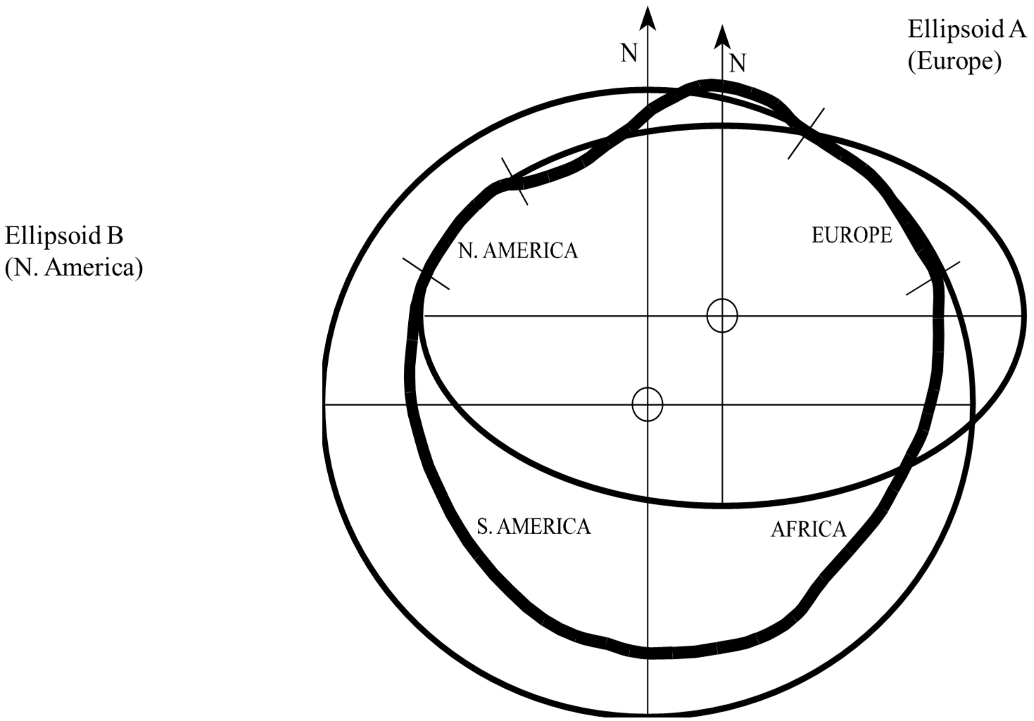
http://www.icsm.gov.au/mapping/web_images/cross_section.jpg http://www.esri.com/news/arcuser/0703/geoid1of3.html

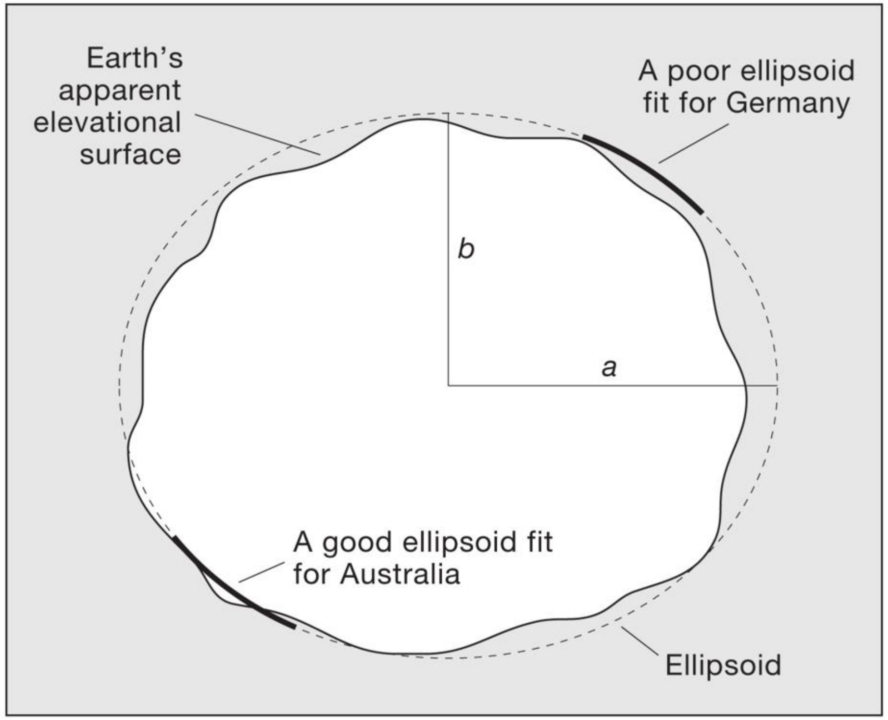
Limiting Complexity: Tradeoffs

- All models are wrong, some models are useful.
- The Geoid, while a much simpler shape than the earth's topographic surface is still very complex.
- For most uses, the simpler ellipsoid works well.
- But… How do we choose the "best" ellipsoid?

Local Ellipsoids

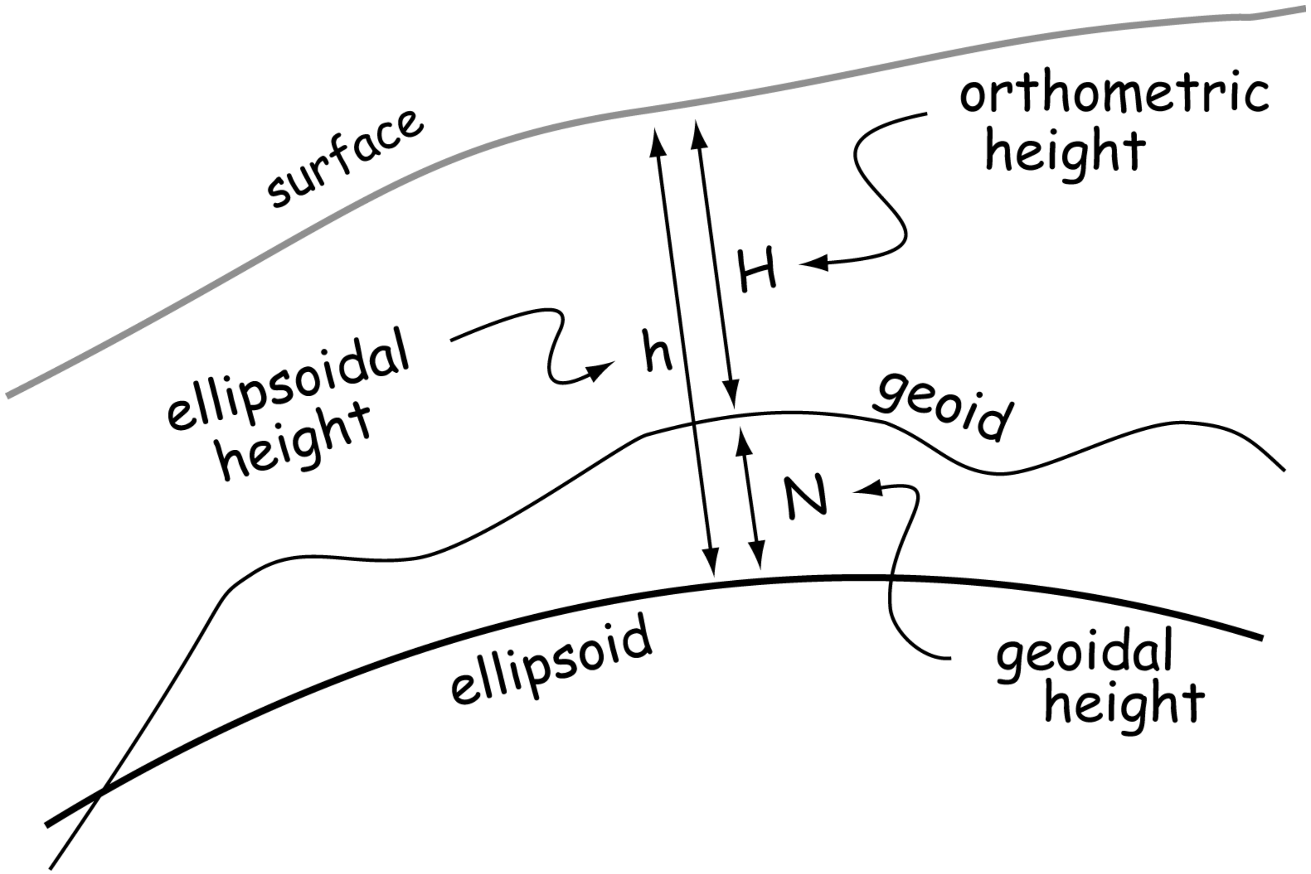
Different Ellipsoids are developed to fit the area of interest accurately over the area of interest





Calculating Ellipsoid Height

- Orthometric height: difference between geoid and surface
- Geoidal height: difference between geoid and ellipsoid



$$h = H + N$$

ellipsoidal height = orthometric height + geoidal height

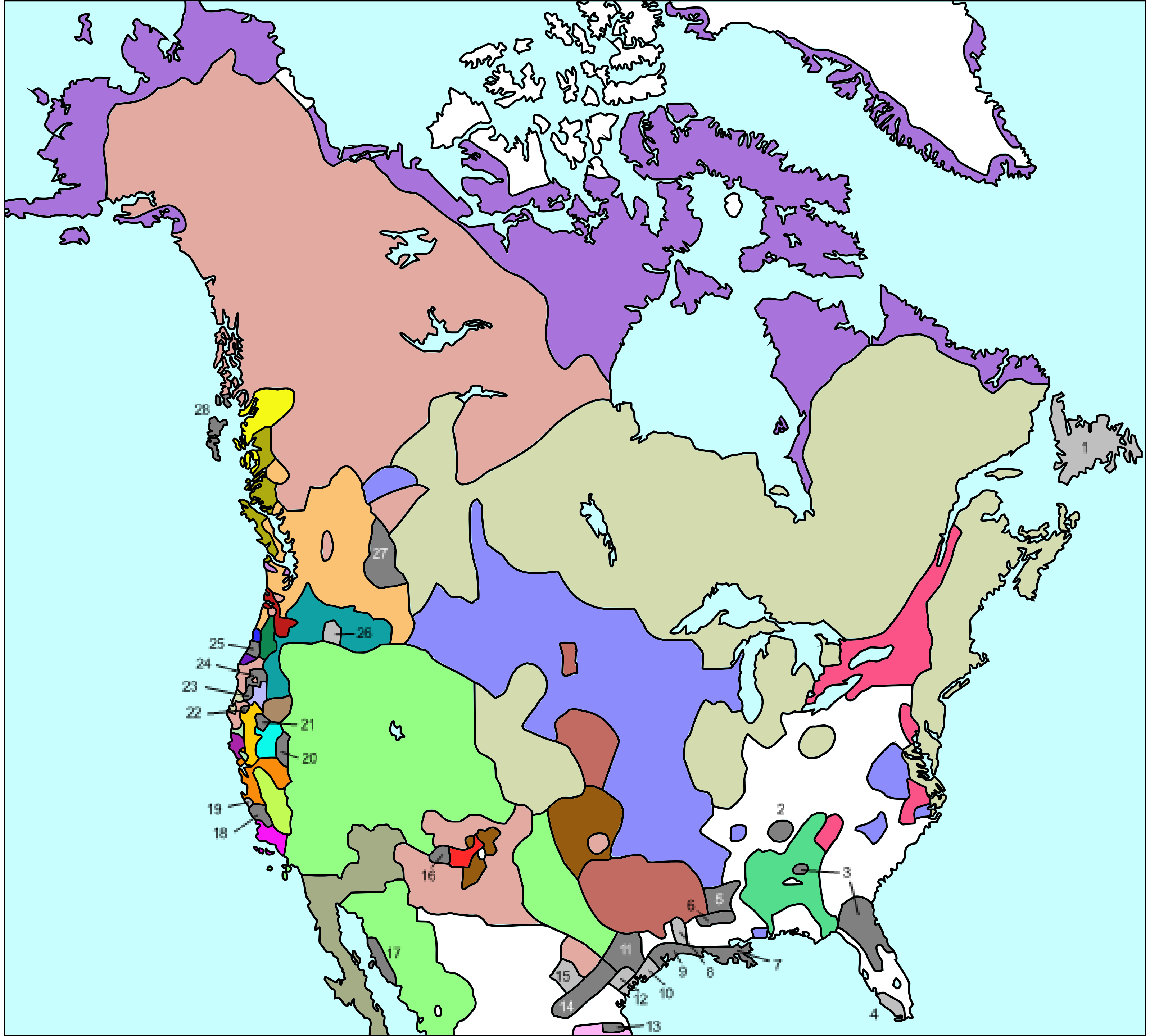
Source: Paul Bolstad. 2012. GIS Fundamentals – A first text on Geographic Information Systems. 4th ed.

What is the Earth's Shape?

It's complicated

A better question:

How can we model the Earth's shape?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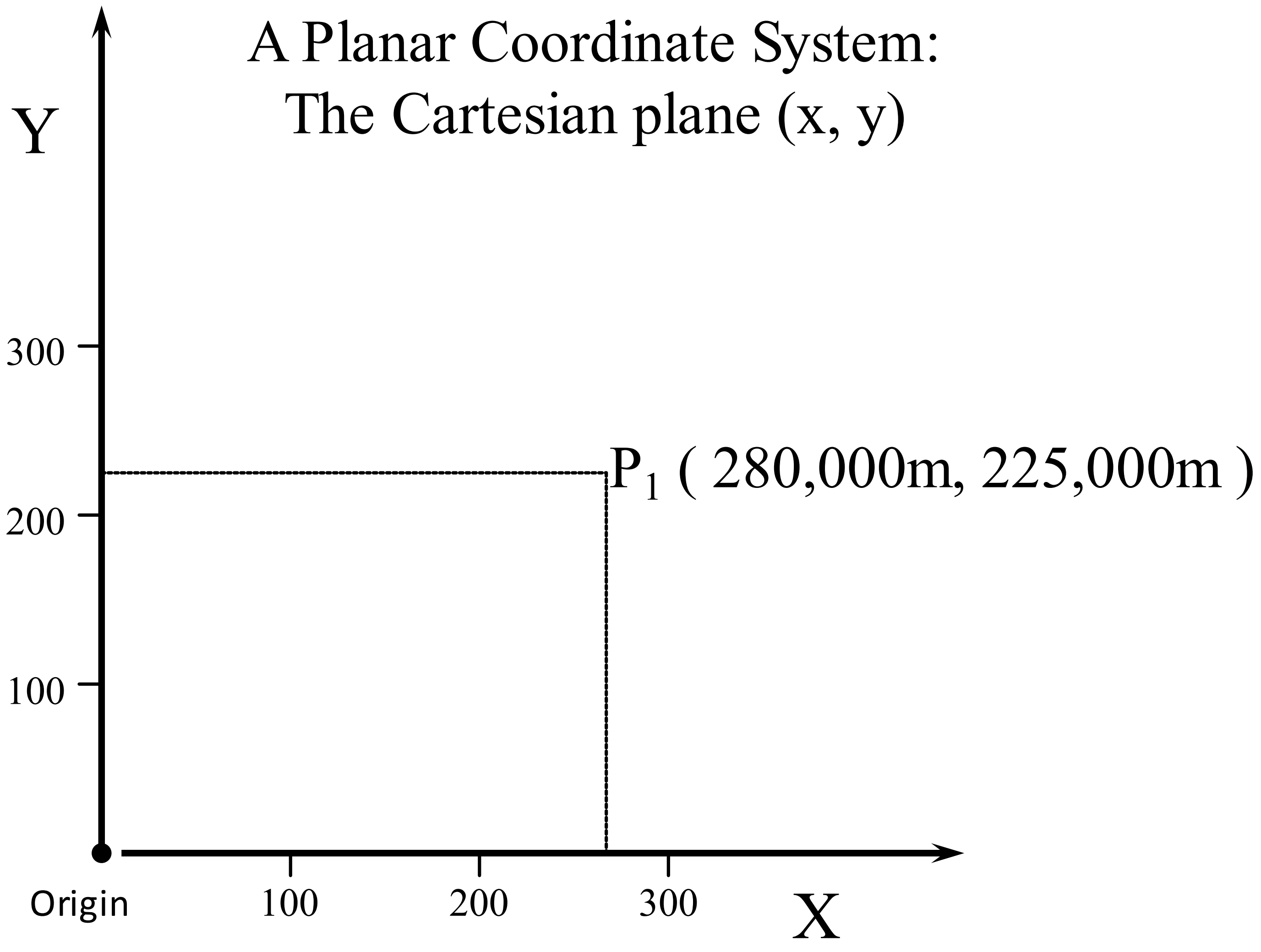
Coordinate Systems

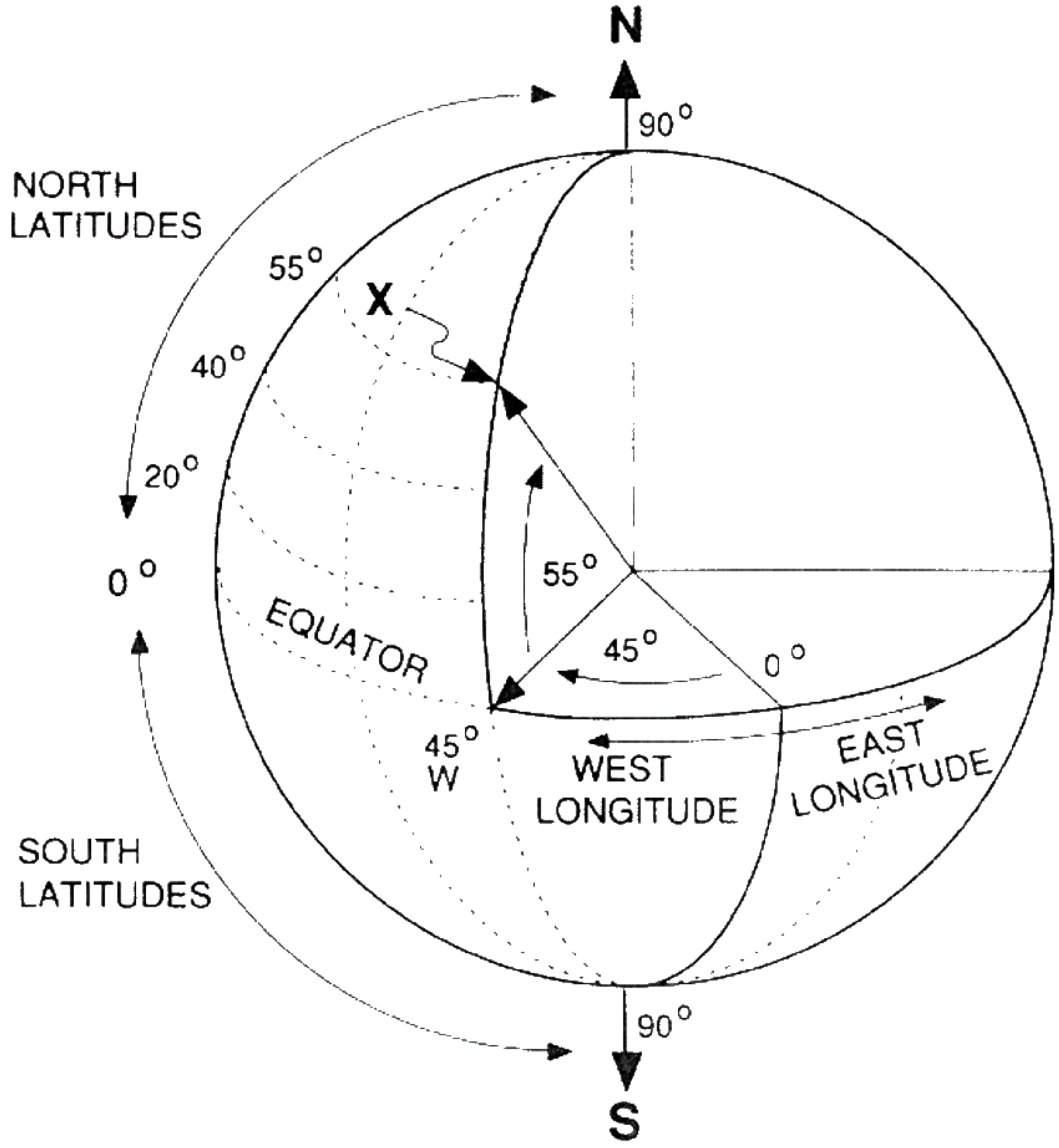
- To be meaningful, spatial data (whether raster or vector) must be associated with a location.
- Coordinate systems are used for the location or registering of those data



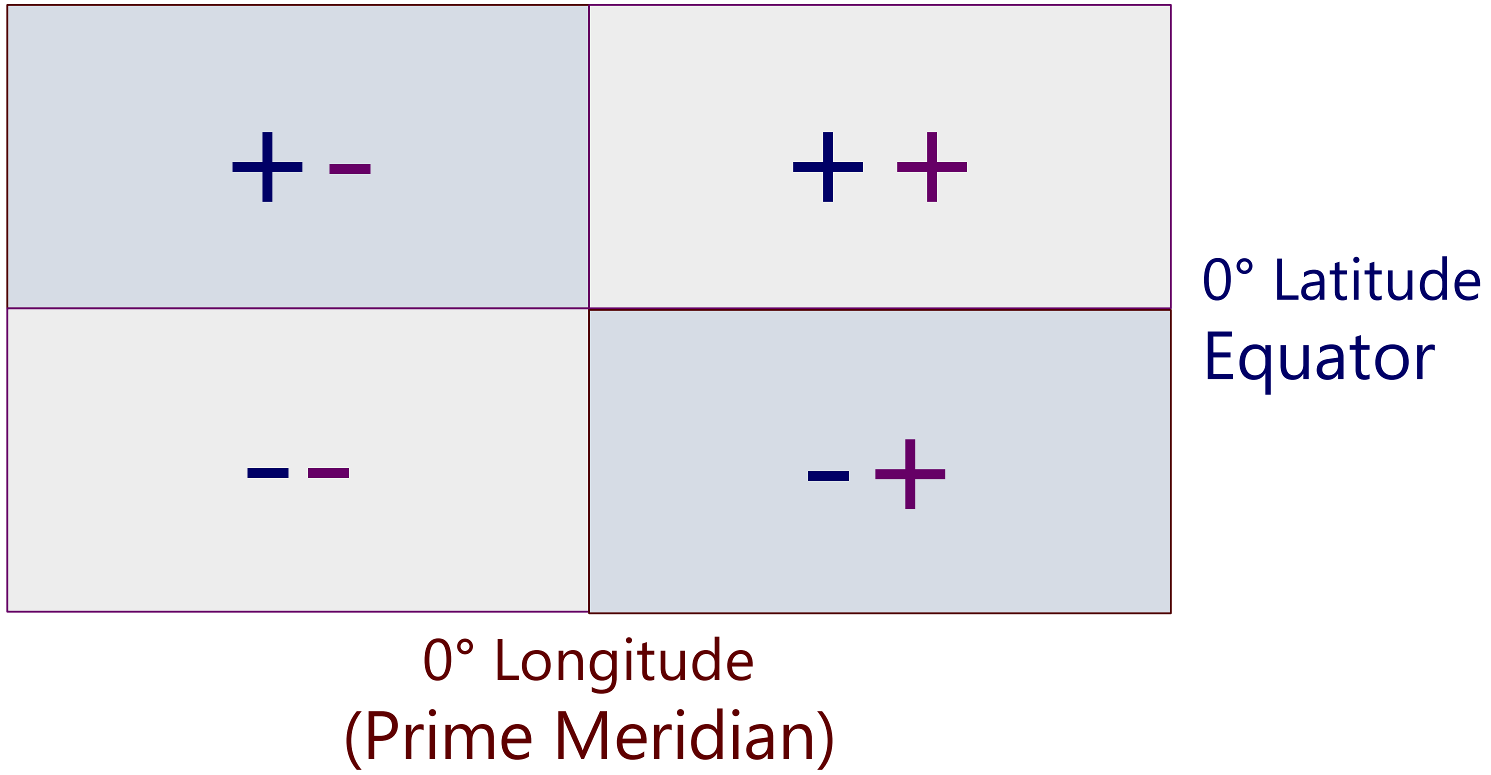
Spherical Coordinate System (2D)

Latitude: degrees (°) North or South of the Equator

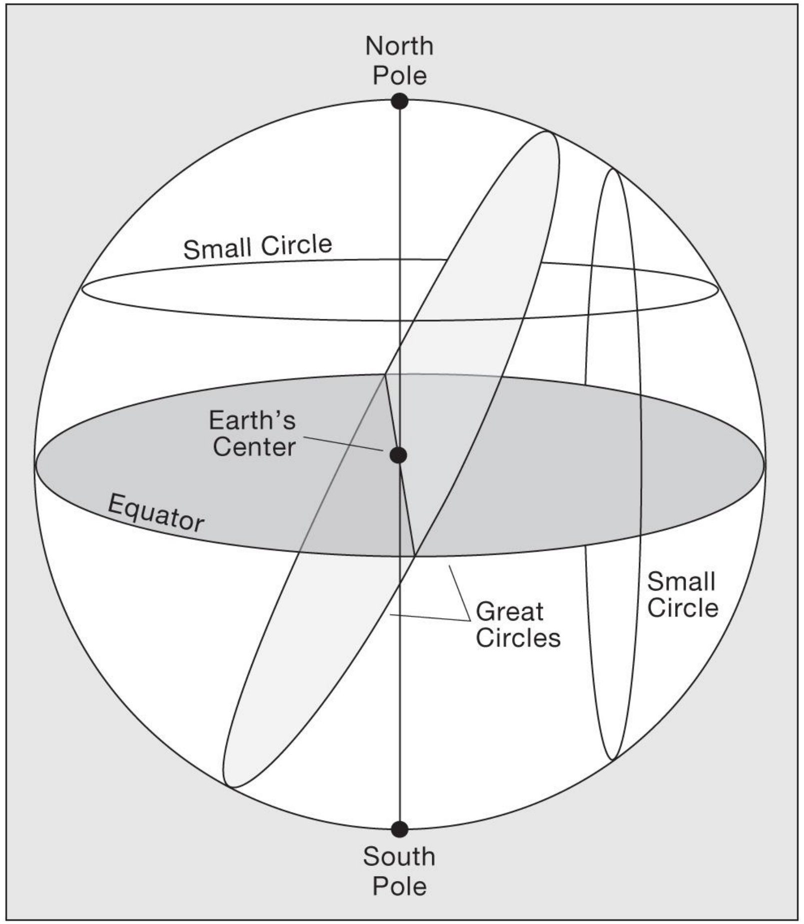
Longitude: degrees (°) East or West of The Prime Meridian

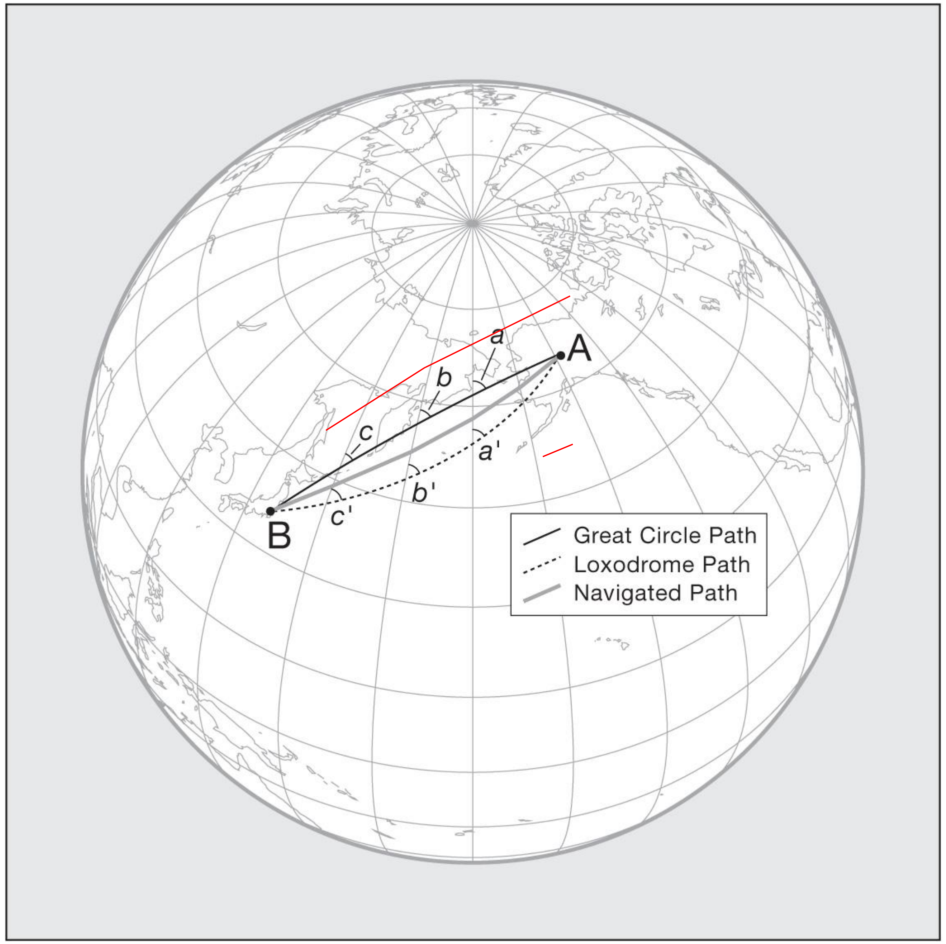


Sign Convention



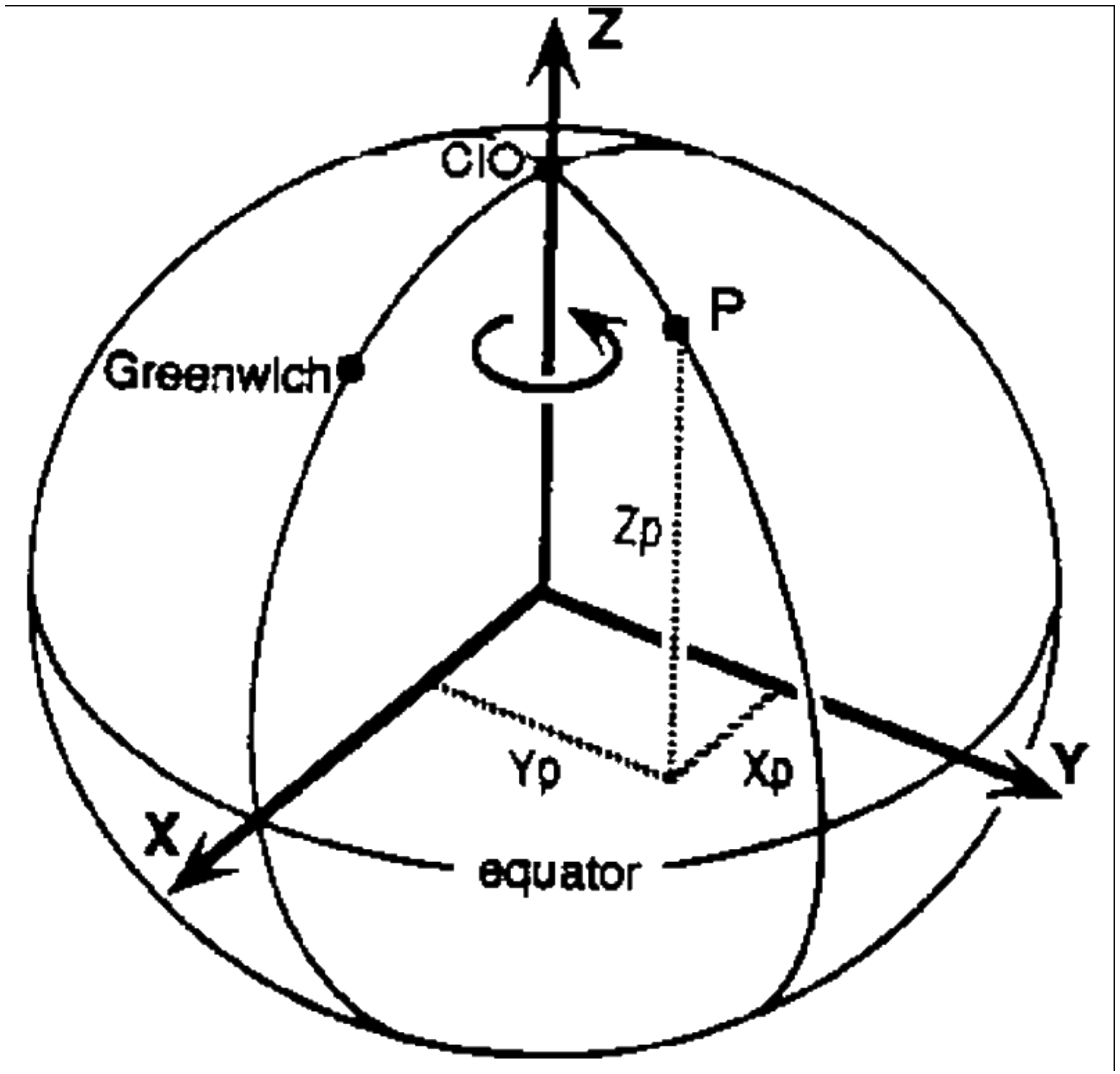
Distance and Directions on the Earth





Geocentric Coordinate System (3D)

- 3-dimensional Terrestrial Reference System, allows referring to positions below or above the Earth's surface



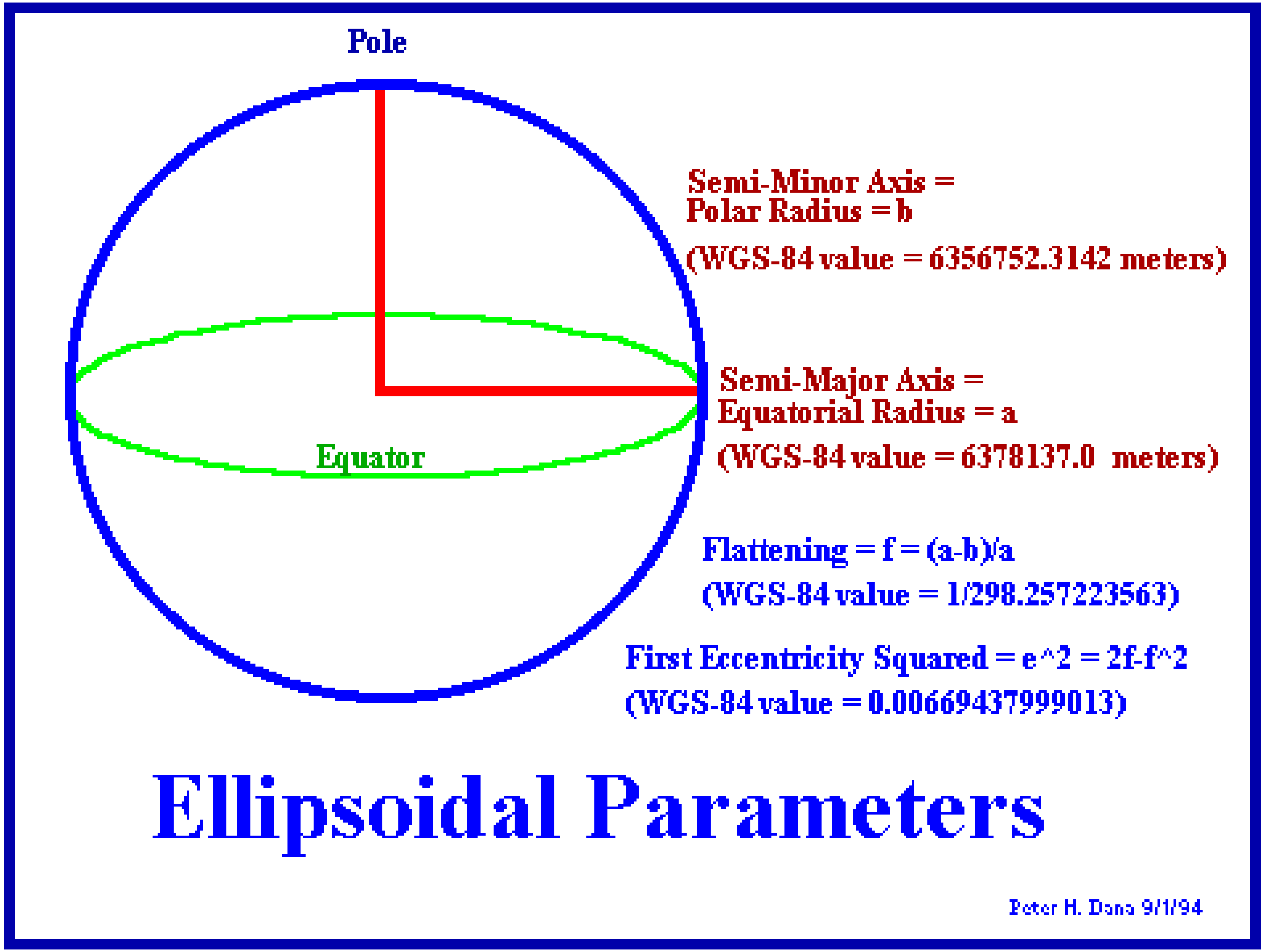
What is a Datum?

*In surveying and geodesy, a **datum** is a reference point or surface against which position measurements are made, and an associated model of the shape of the earth for computing positions*

http://en.wikipedia.org/wiki/Geodetic_system

- A geodetic datum is a mathematical model of the earth upon which geodetic computations are based.
- A datum is a reference system with two components:
  - A specified **elliposid with a spherical coordinate system** and an **origin**
  - A set of highly accurate surveyed **points** and lines to anchor the ellipsoid
- There are *Regional* and *Global* Datums.

A **DATUM** is a model of the Earth as an ellipsoid.

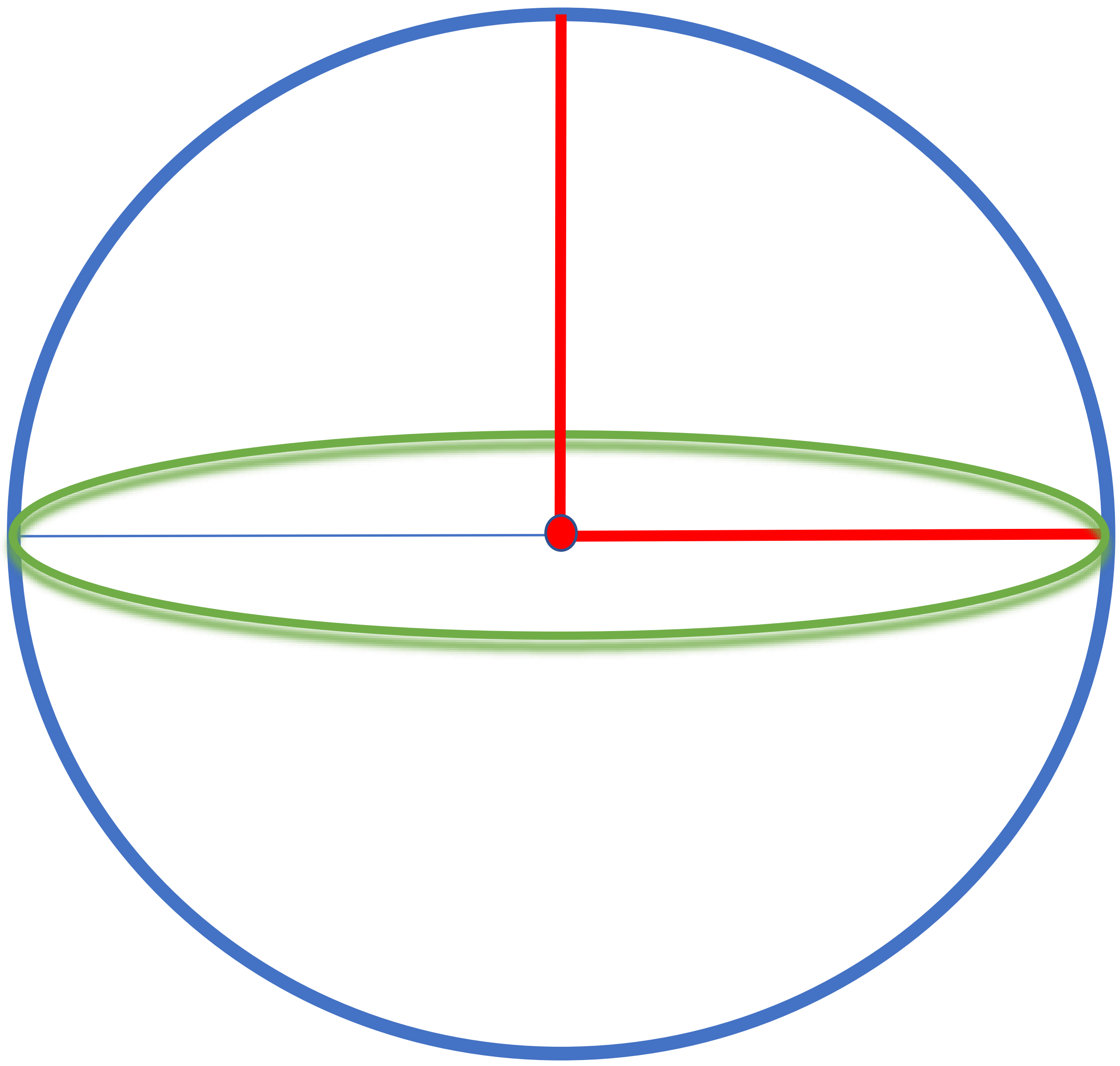


Depending on where you are on Earth, you might change your definition of the spheroid

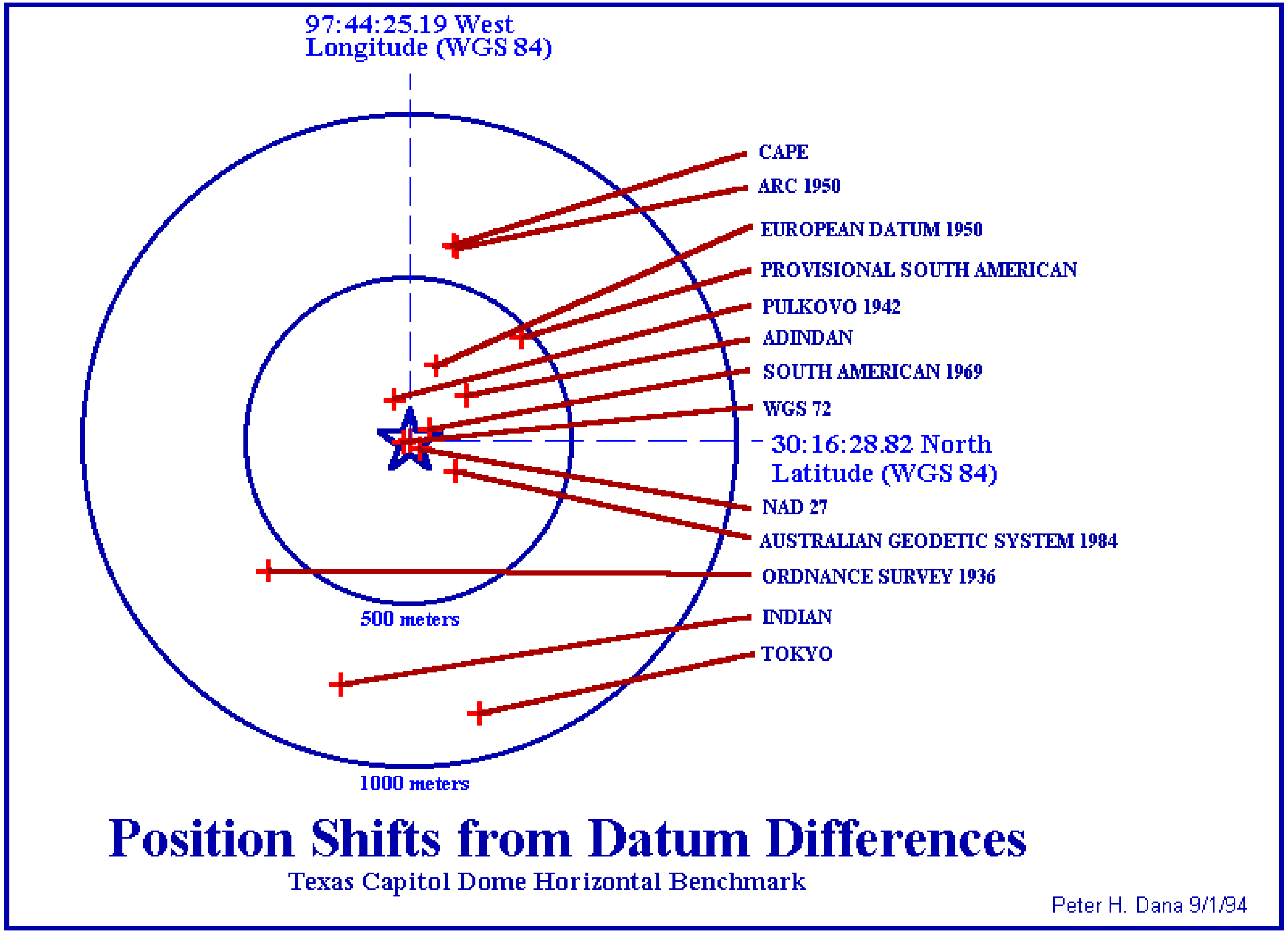
- A **DATUM** is a model of the Earth as an ellipsoid that is anchored to specific locations on or below the Earth's surface.

- Example datums:
- WGS84 (World geodetic system)
- NAD27 (North American datum)

- A **DATUM IS NOT** a coordinate system or projection.

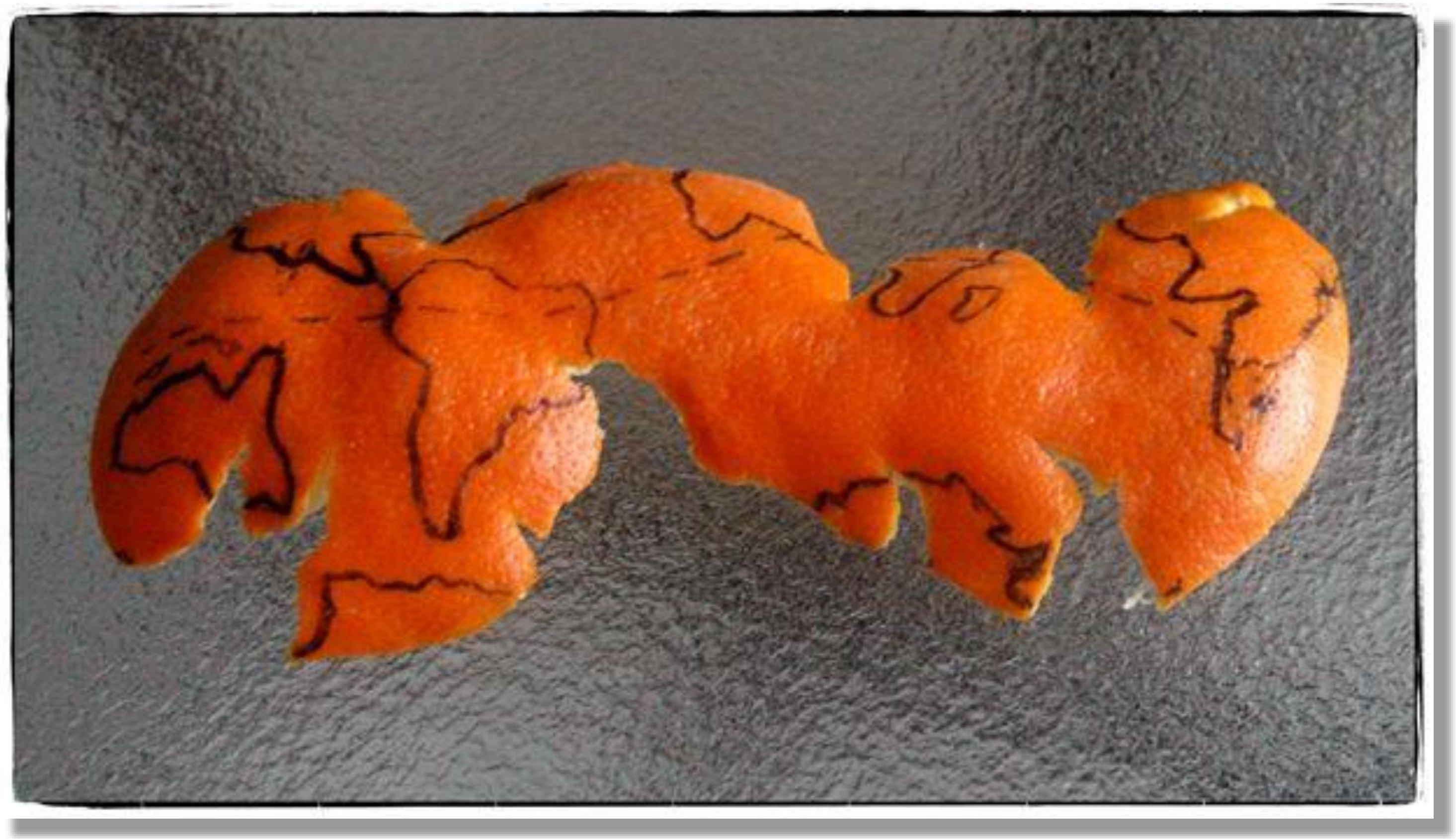


Does it Make a Difference?



How can we represent a 3D surface on a 2D map?

Write your name on the orange, then peel it to make your name flat.
(yes, eat the orange)



The Classic Orange Peel

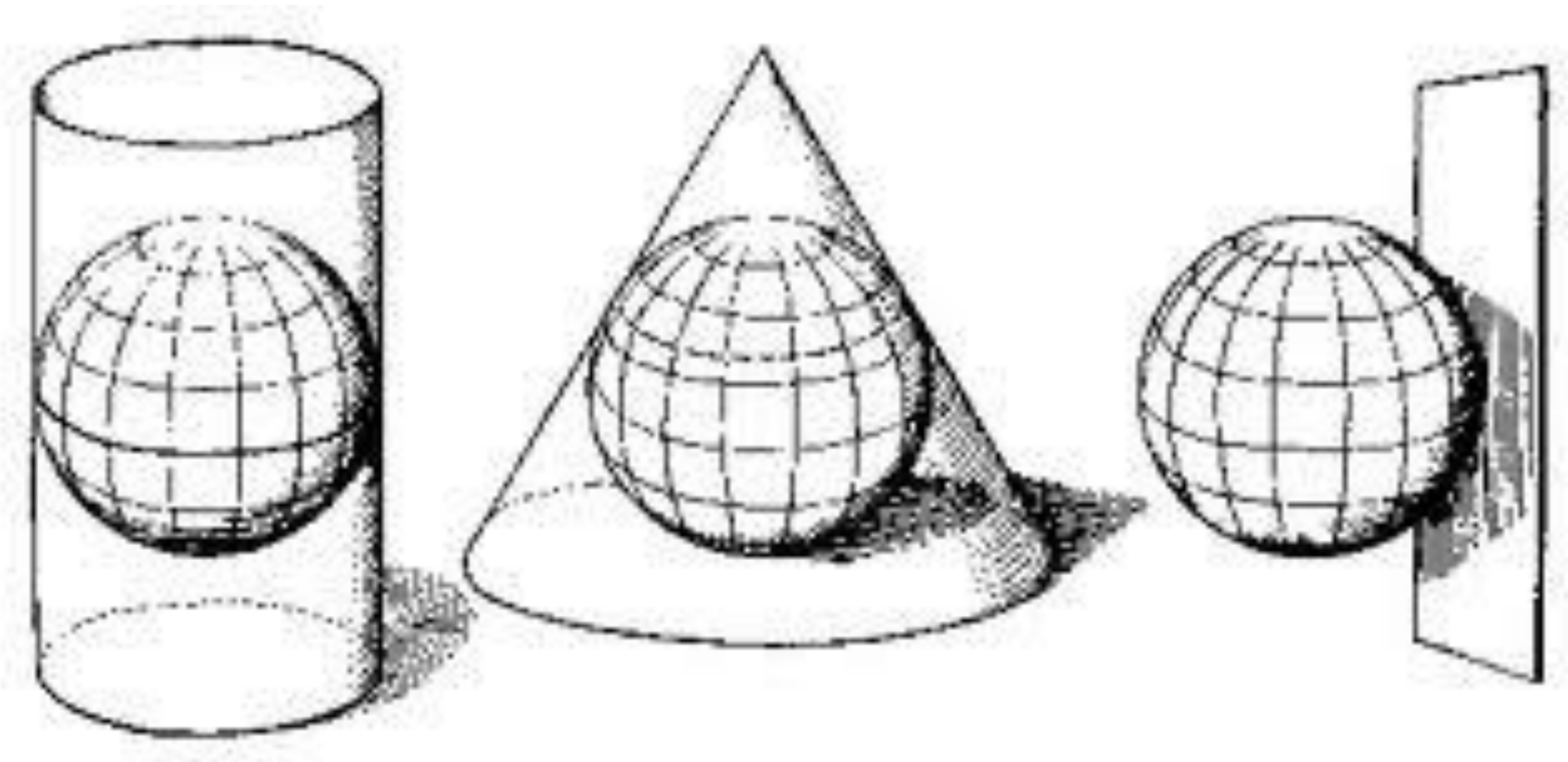
https://s-media-cache-ak0.pinimg.com/736x/2d/81/fc/2d81fcafacdc11ec04f34d1b1c587954.jpg

Intro to Projections with Hanna Fry

- https://www.youtube.com/watch?v=D3tdW9l1690&feature=emb_logo&ab_channel=Numberphile

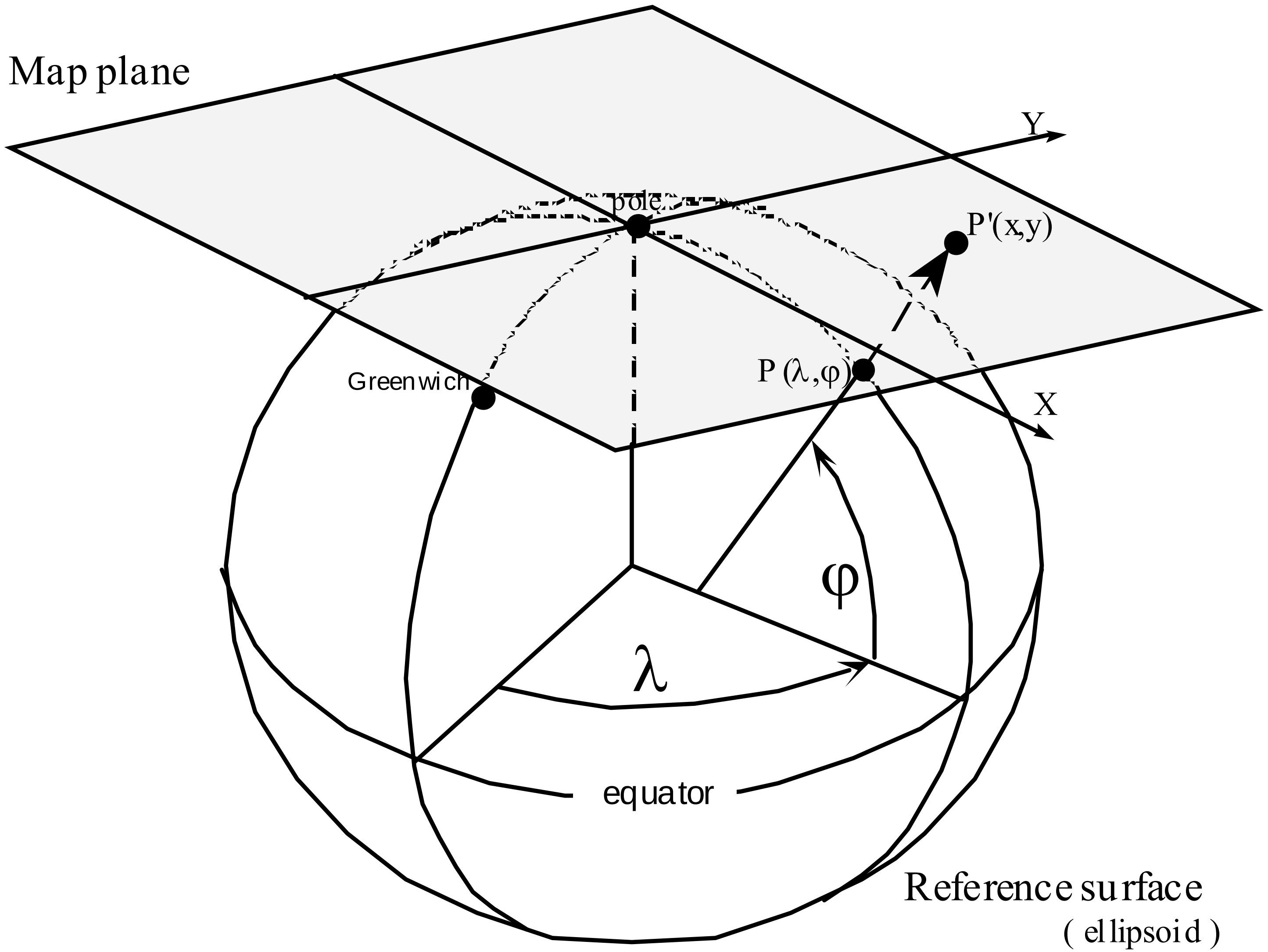
Three main types of map projections

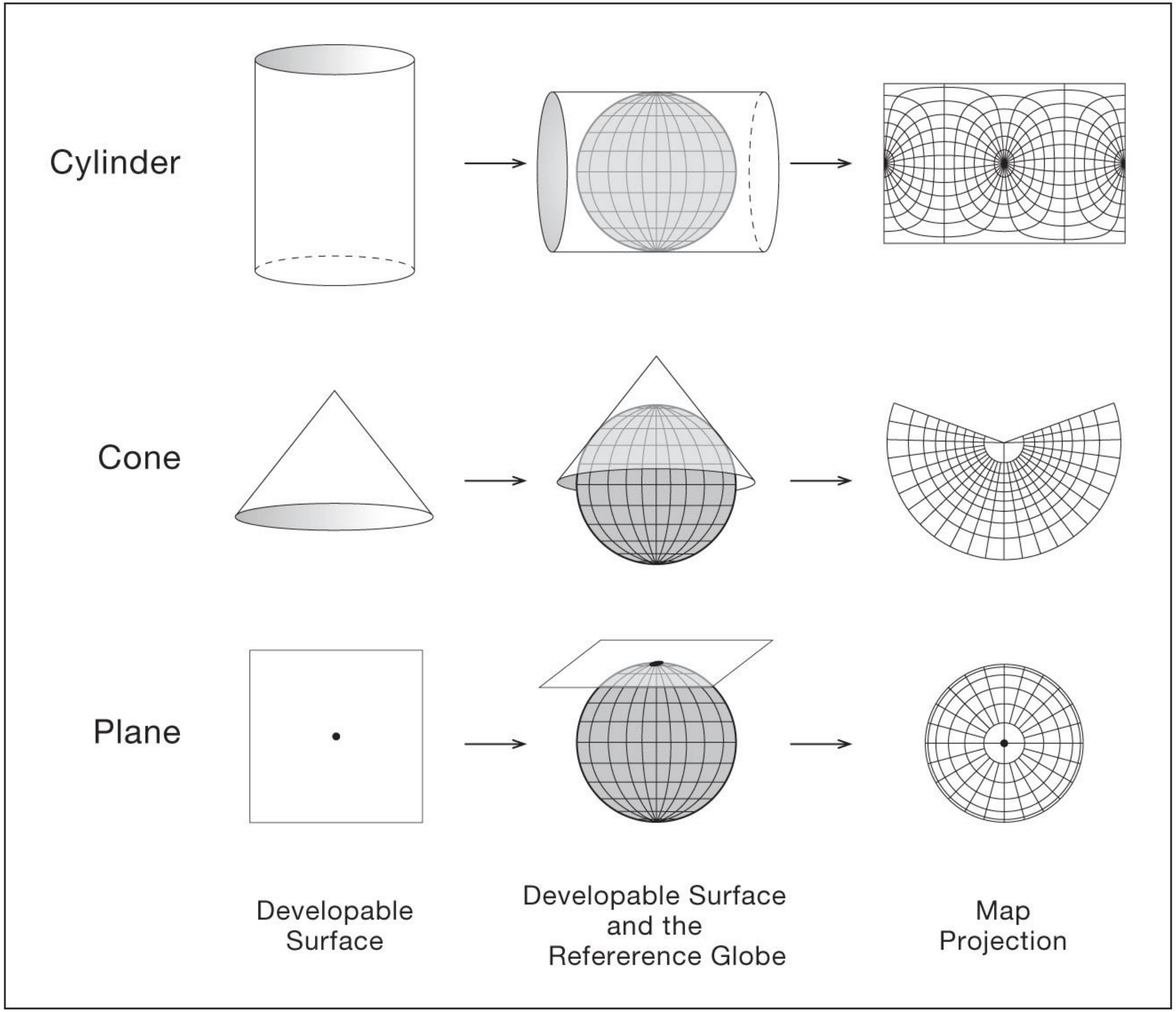
Cylindrical, Conic, Azimuthal



The Map Projection Principle

1. Reference globe
2. Developable surface
   - Cylinders
   - Cones
   - Planes




Cylinder
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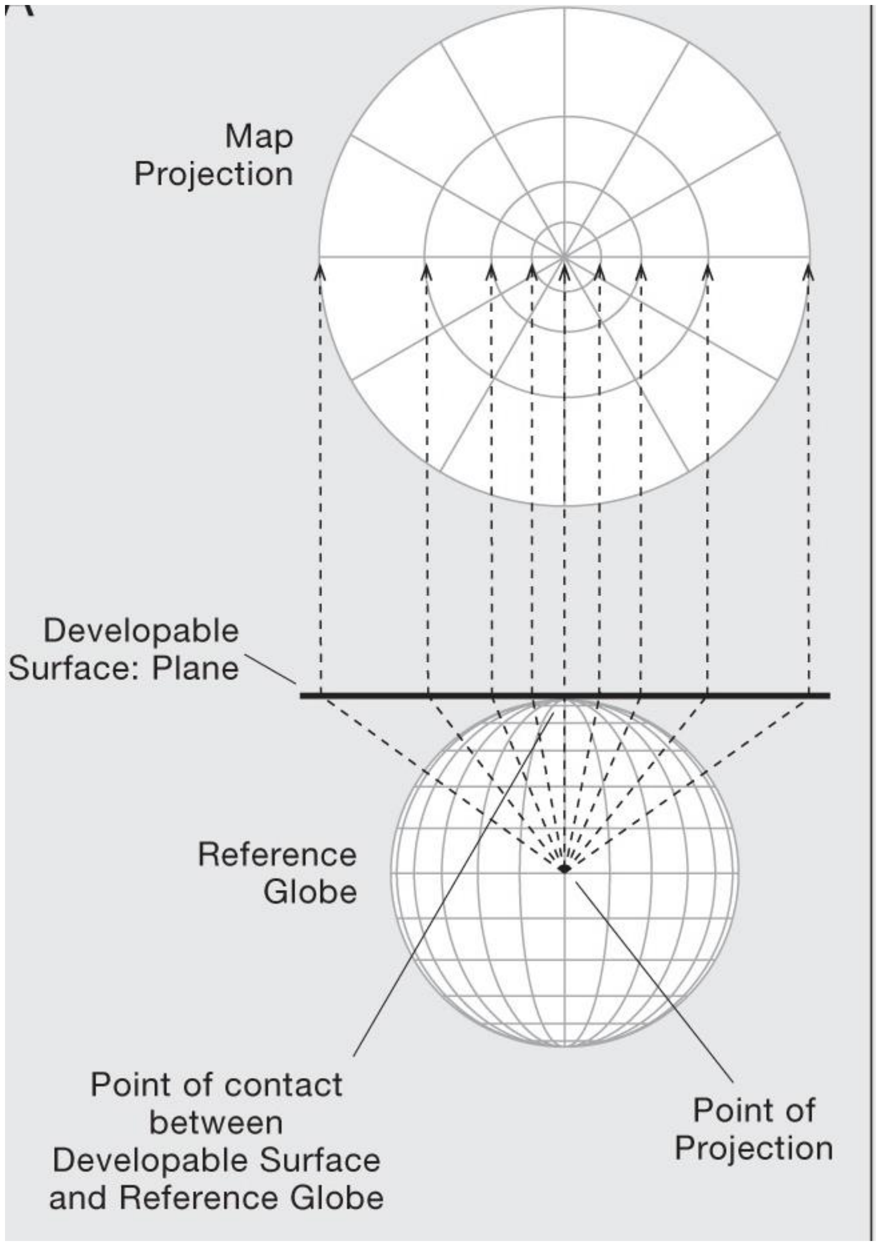
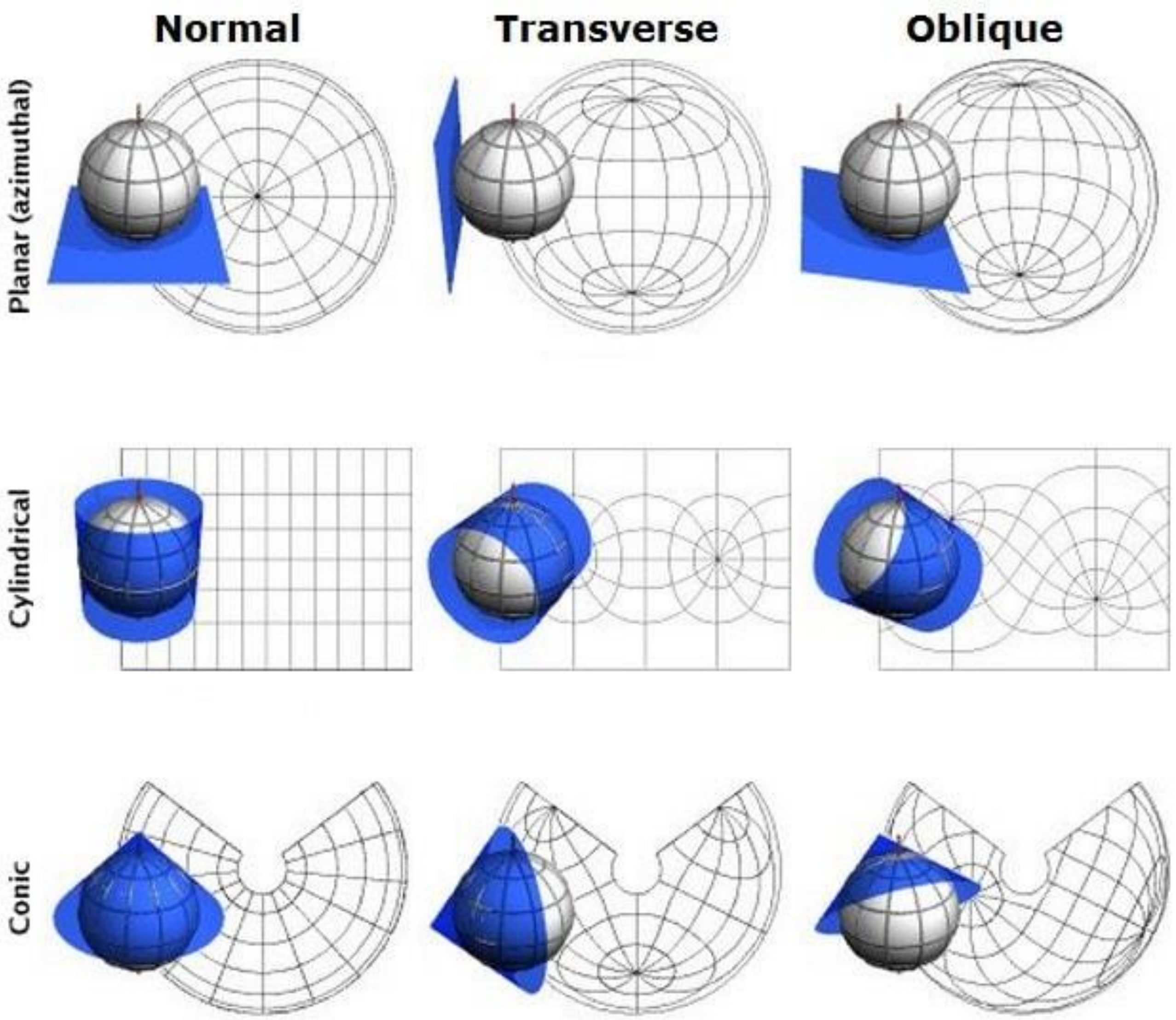
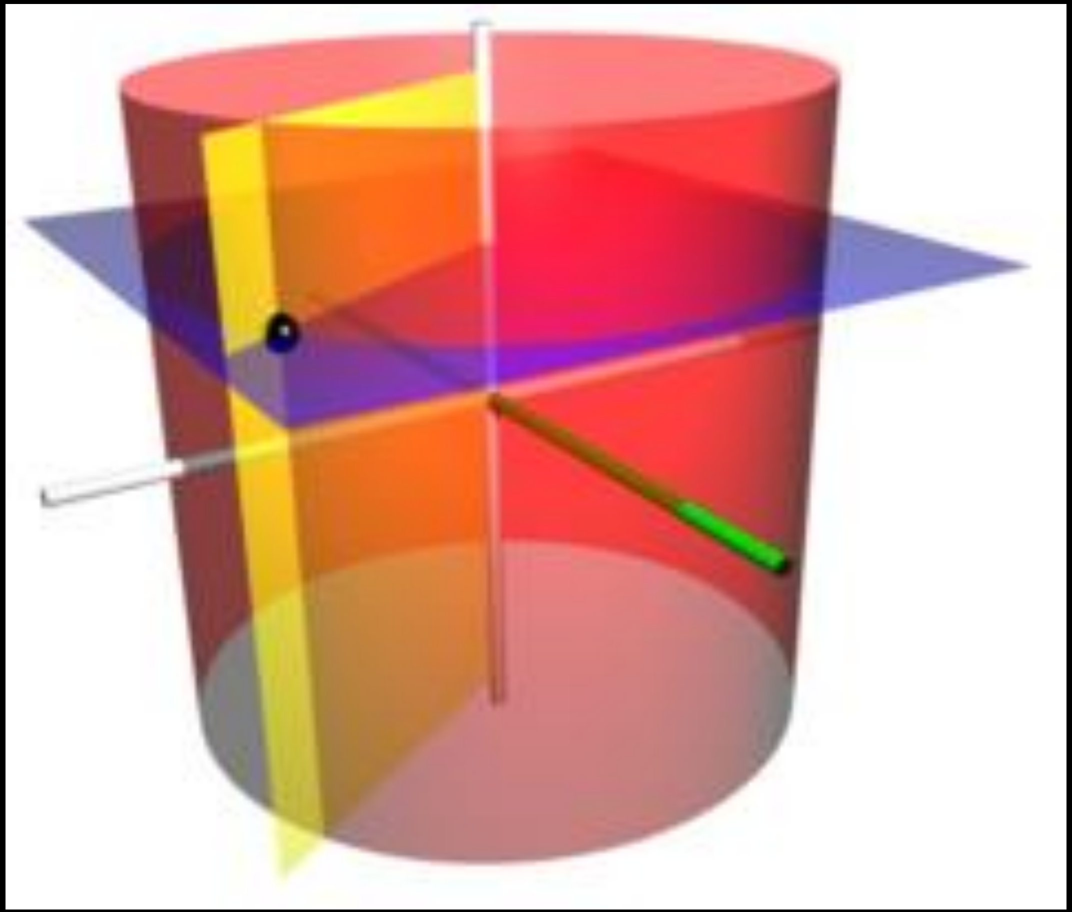
and the
Refererence Globe
Map
Projection


Map
Projection
Developable
Surface: Plane
Reference
Globe
Point of contact
between
Developable Surface
and Reference Globe
Point of
Projection

• Class and aspect

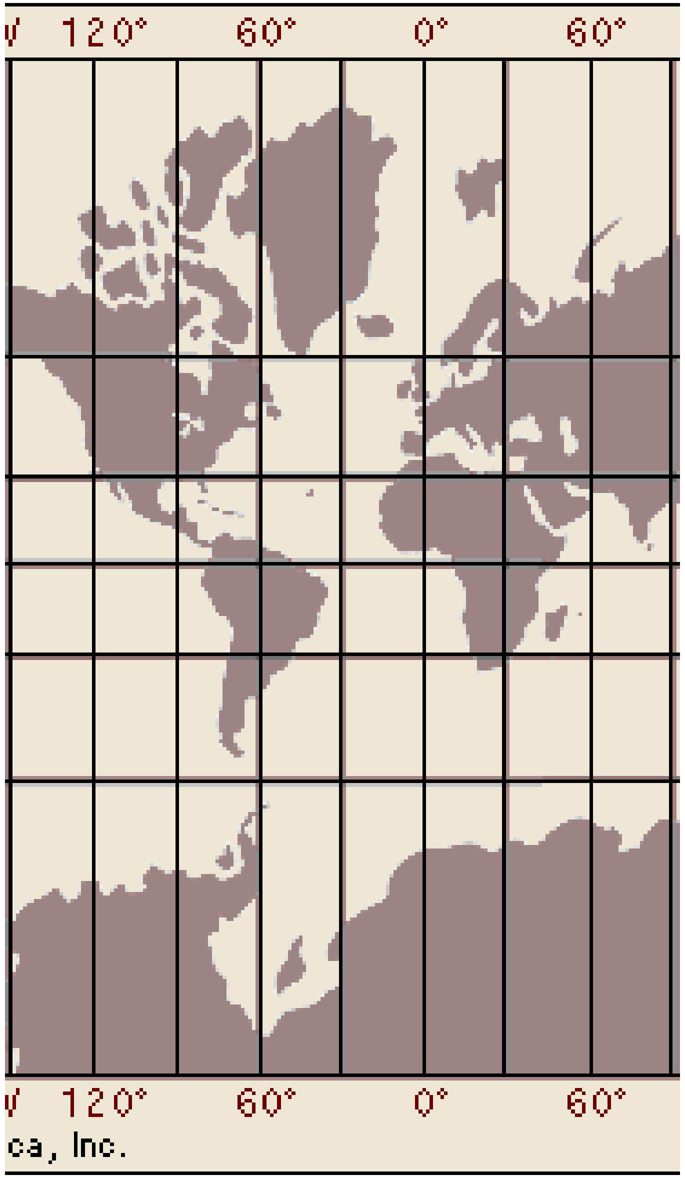


Cylindrical Projections

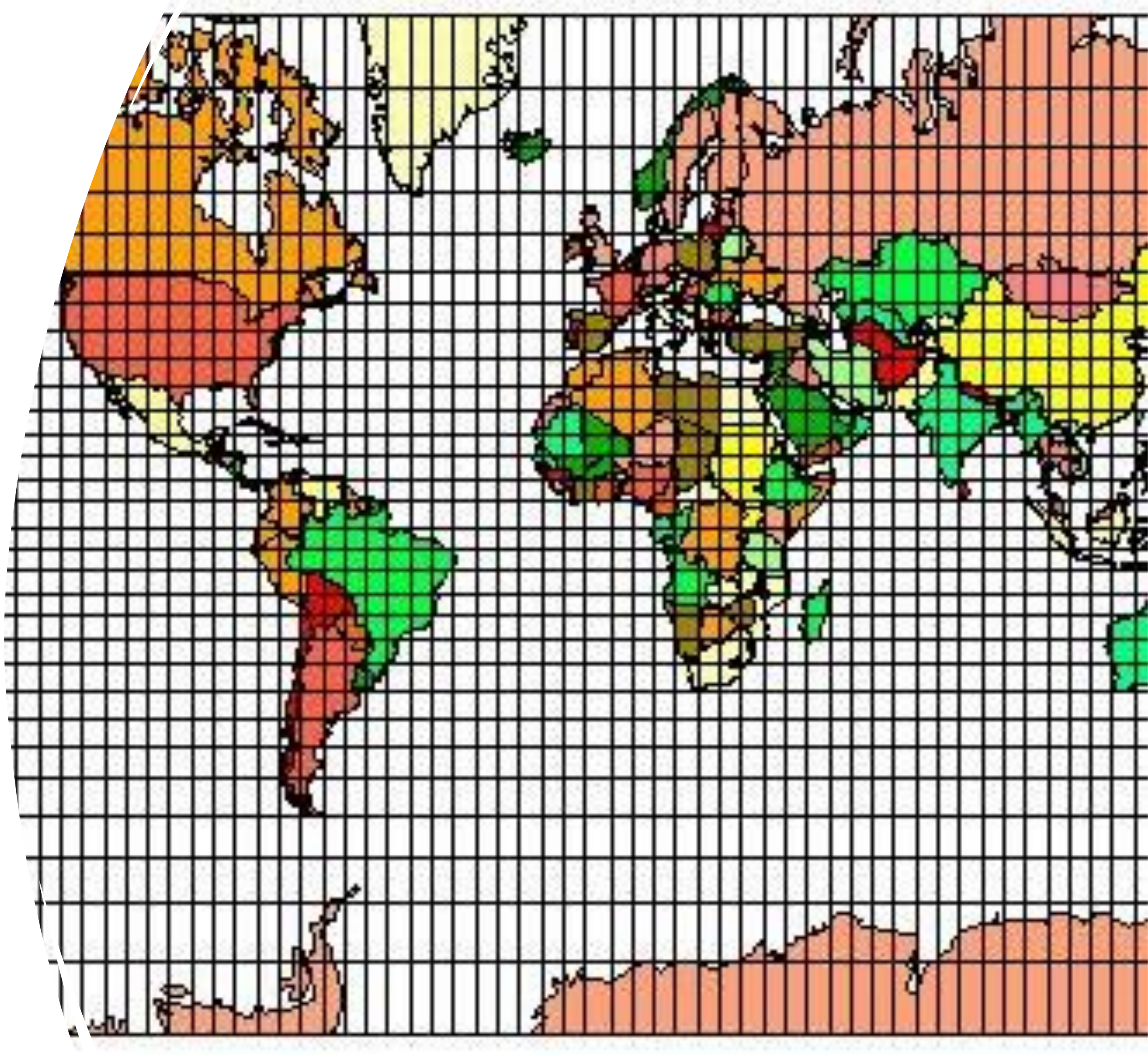


Mercator Projections

- Developed by Dutch cartographer Gerardus Mercator in 1569
- Preserves shape & direction
- Used widely for navigation charts because direction is preserved.



What parts of the Earth look best in Mercator?

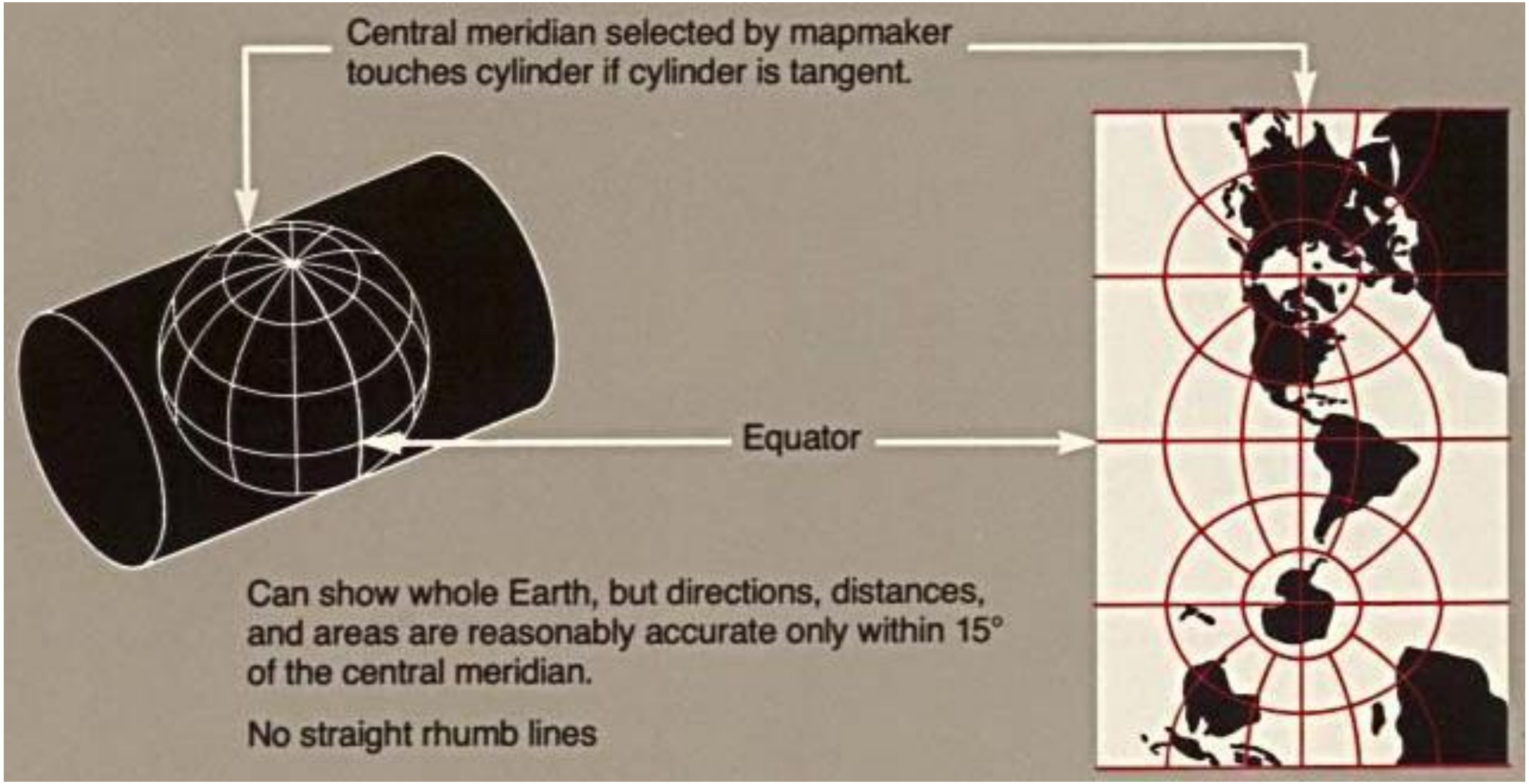


Cartographers for social equality

To Mercator or not to Mercator

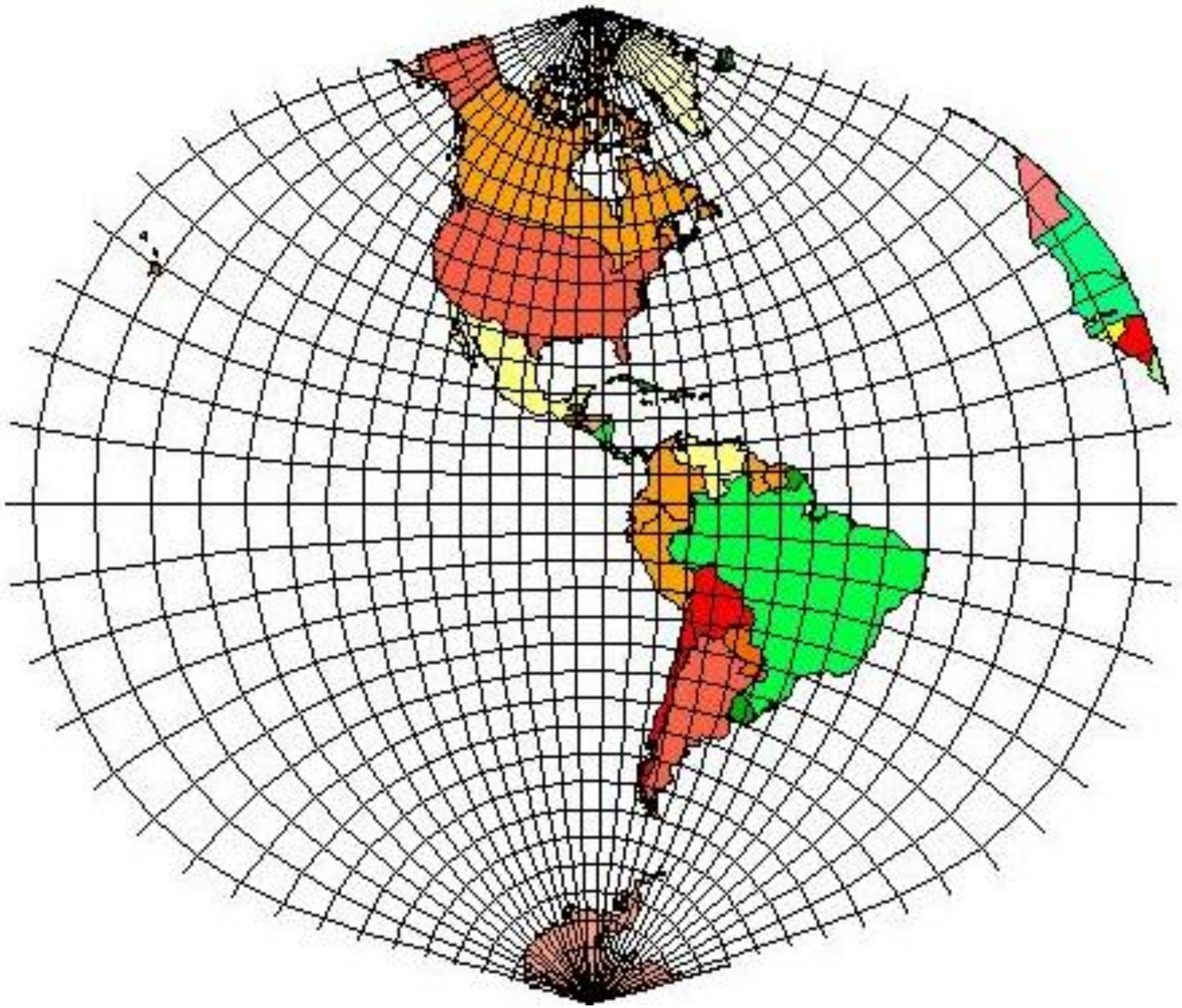
- March 2017 – Massachusetts became the first state to officially adopt a Gall-Peters projection in all K-12 classrooms
- Gall-Peters is an equal-area cylindrical projection.

https://www.youtube.com/watch?v=vVX-PrBRtTY



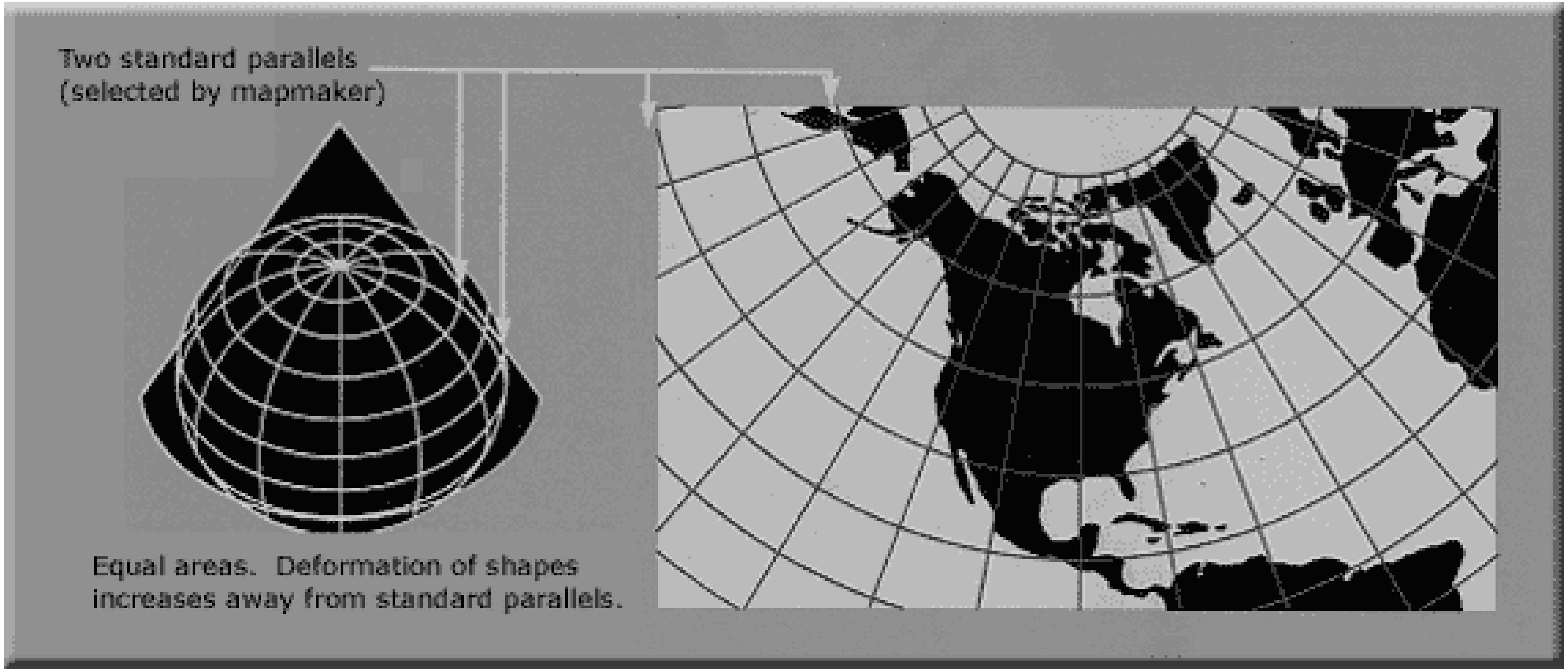
Transverse Mercator

When would we want to use transverse Mercator?

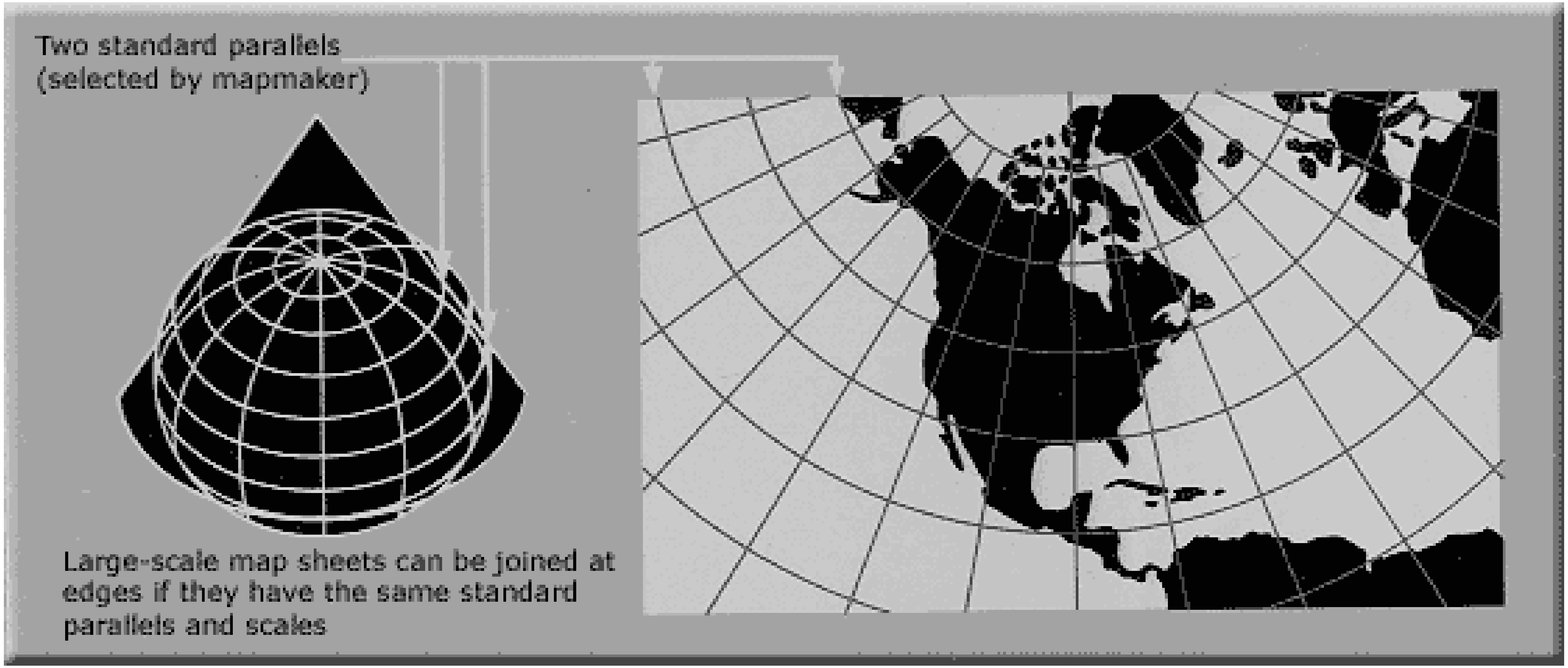


Conic Projections

Albers Equal Area Conic

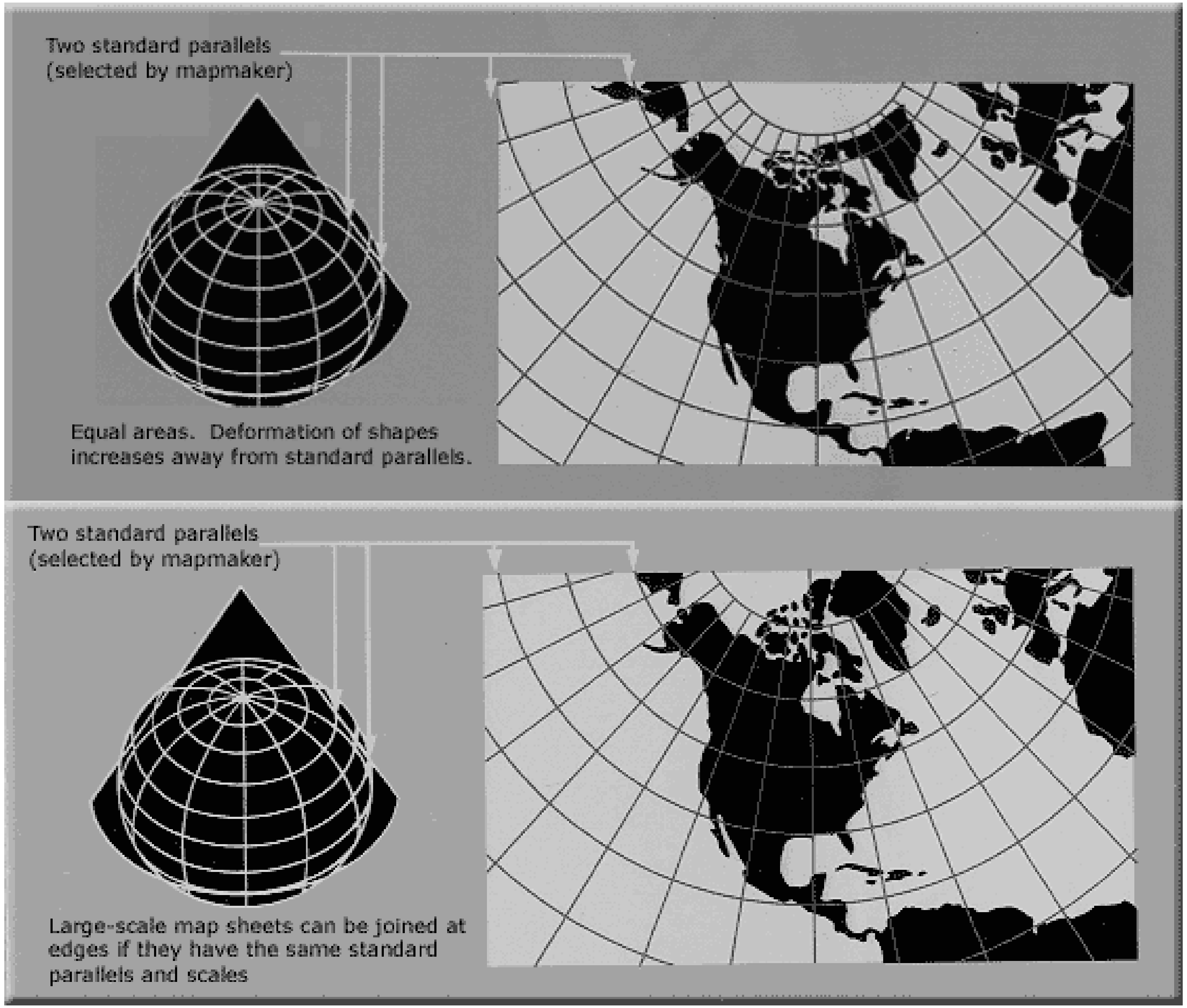


Lambert Conformal Conic



Conic: Conformal or Equal Area

- Equal area: Areas of shapes are (mostly) preserved)
  - North and south parallels are squished
- Conformal: Shapes of objects are (mostly) preserved.
  - Central parallels more closely spaced

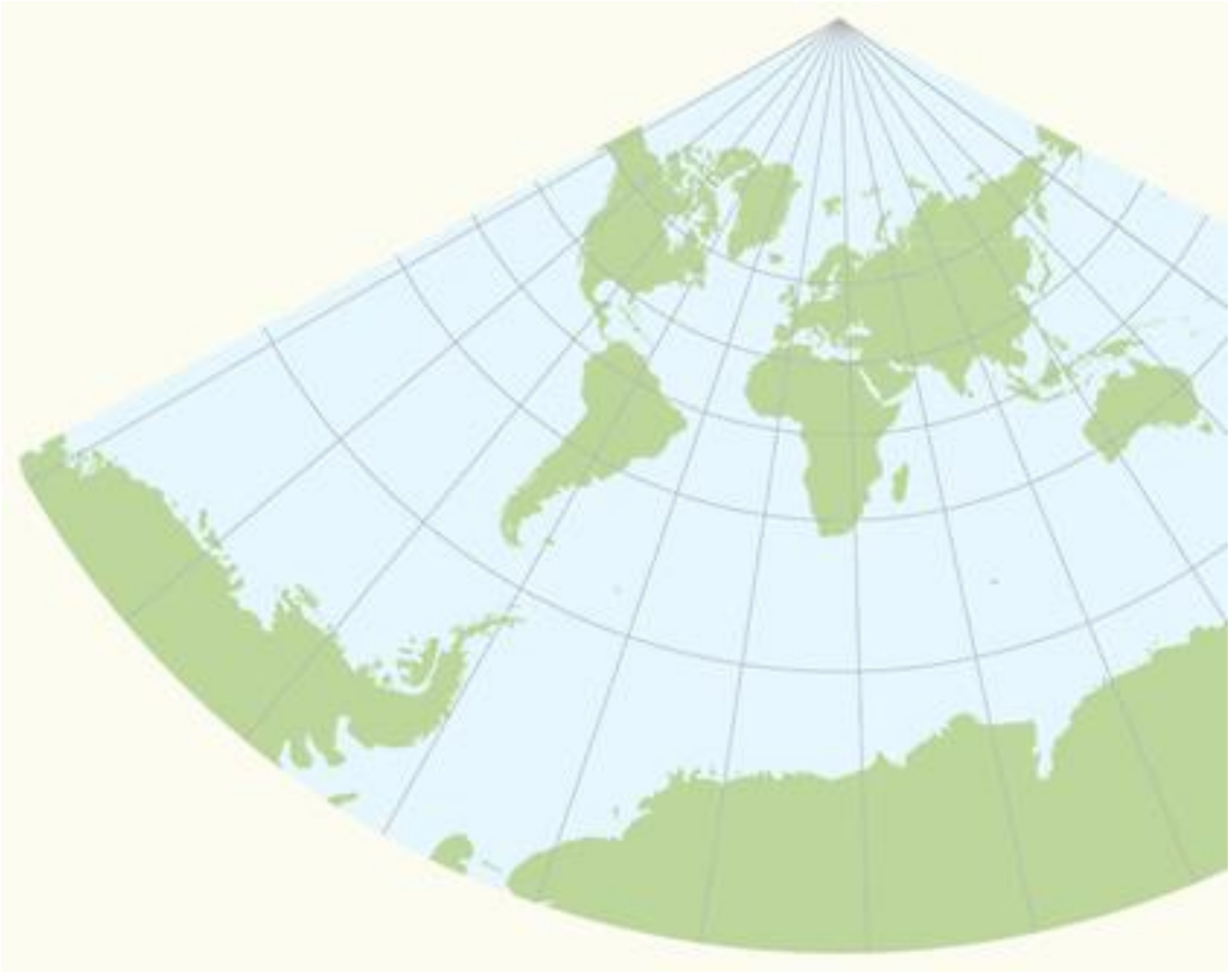


MassGIS uses Lambert Conformal Conic

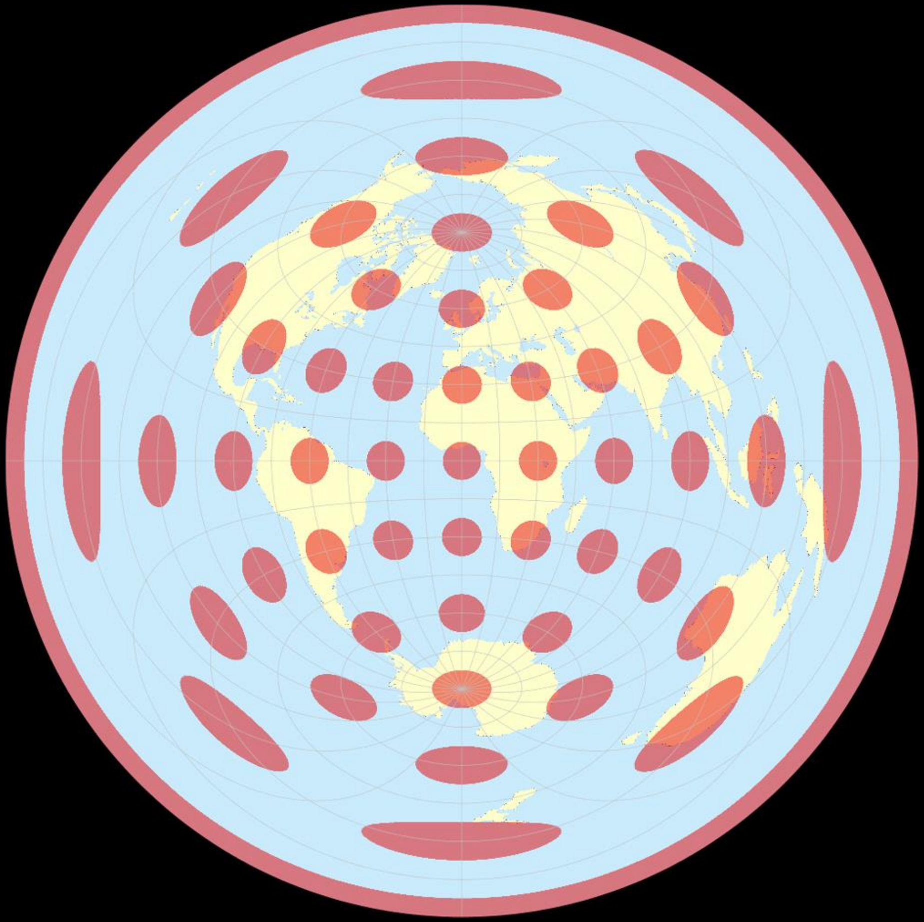
When would we want to use a conic projection?

When would we want to use a conic projection?

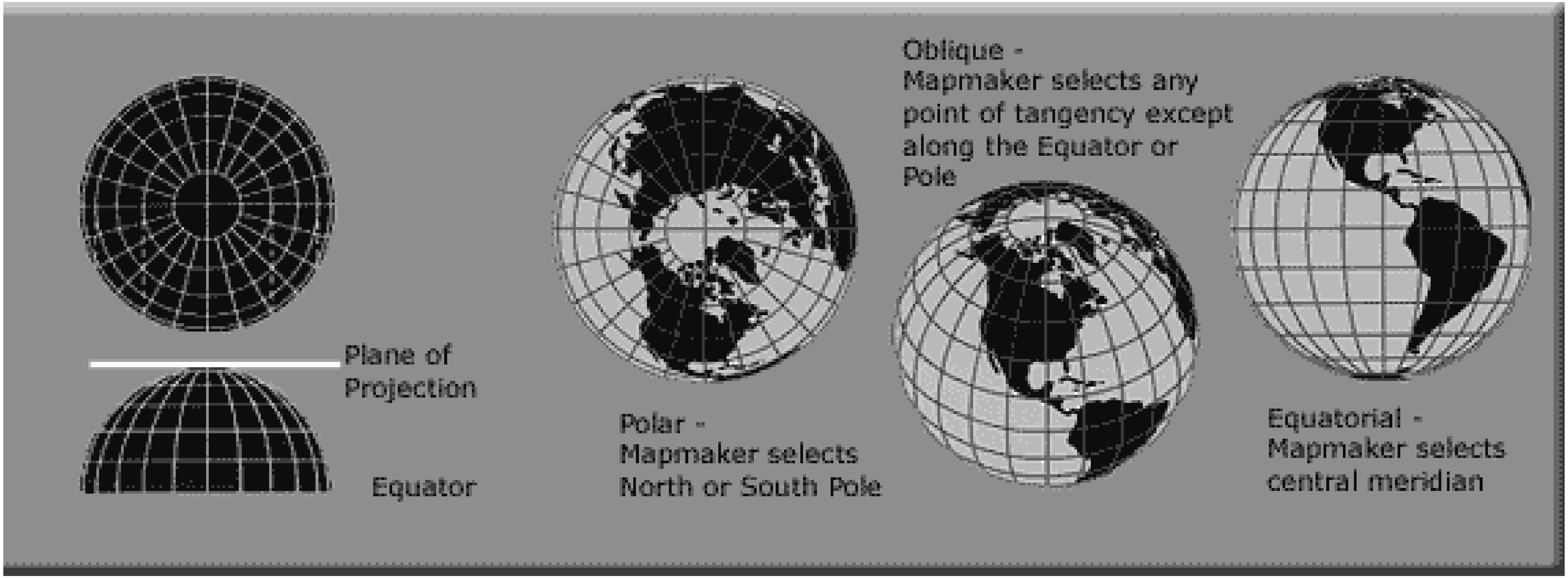
- Mid-latitudes
- East/West oriented regions



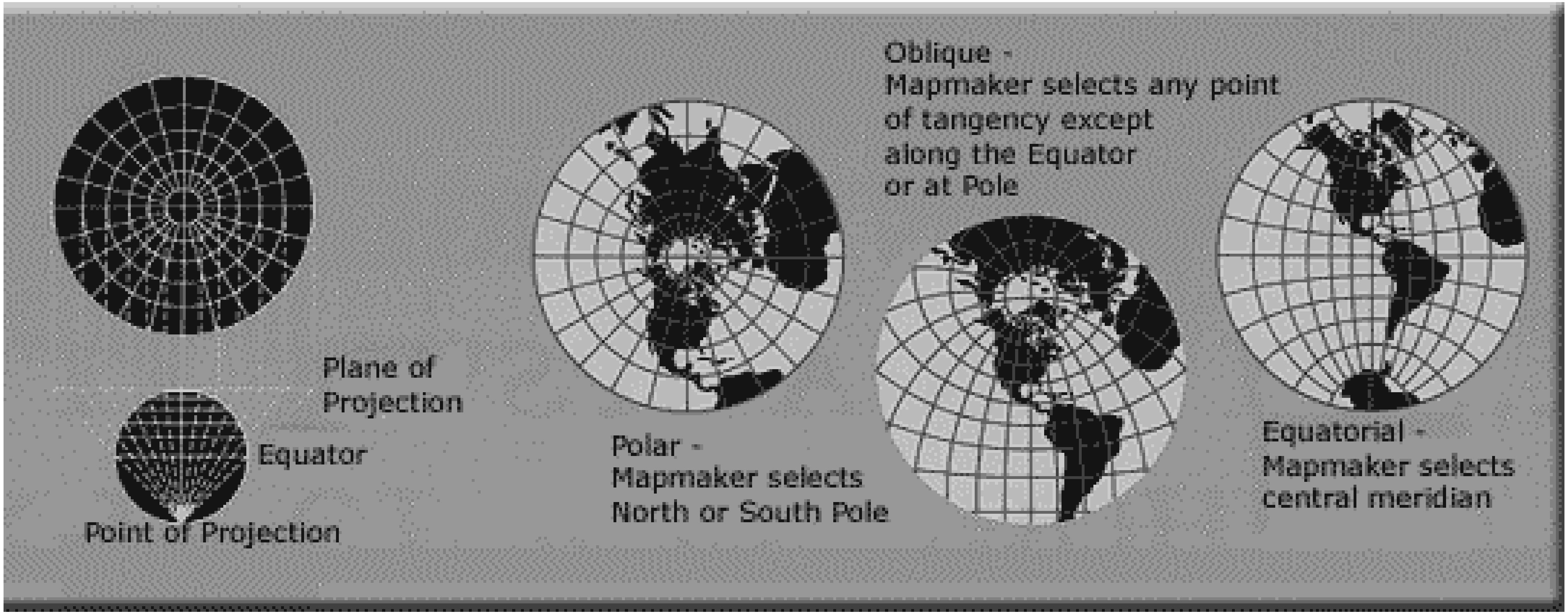
Azimuthal (planar) Projections



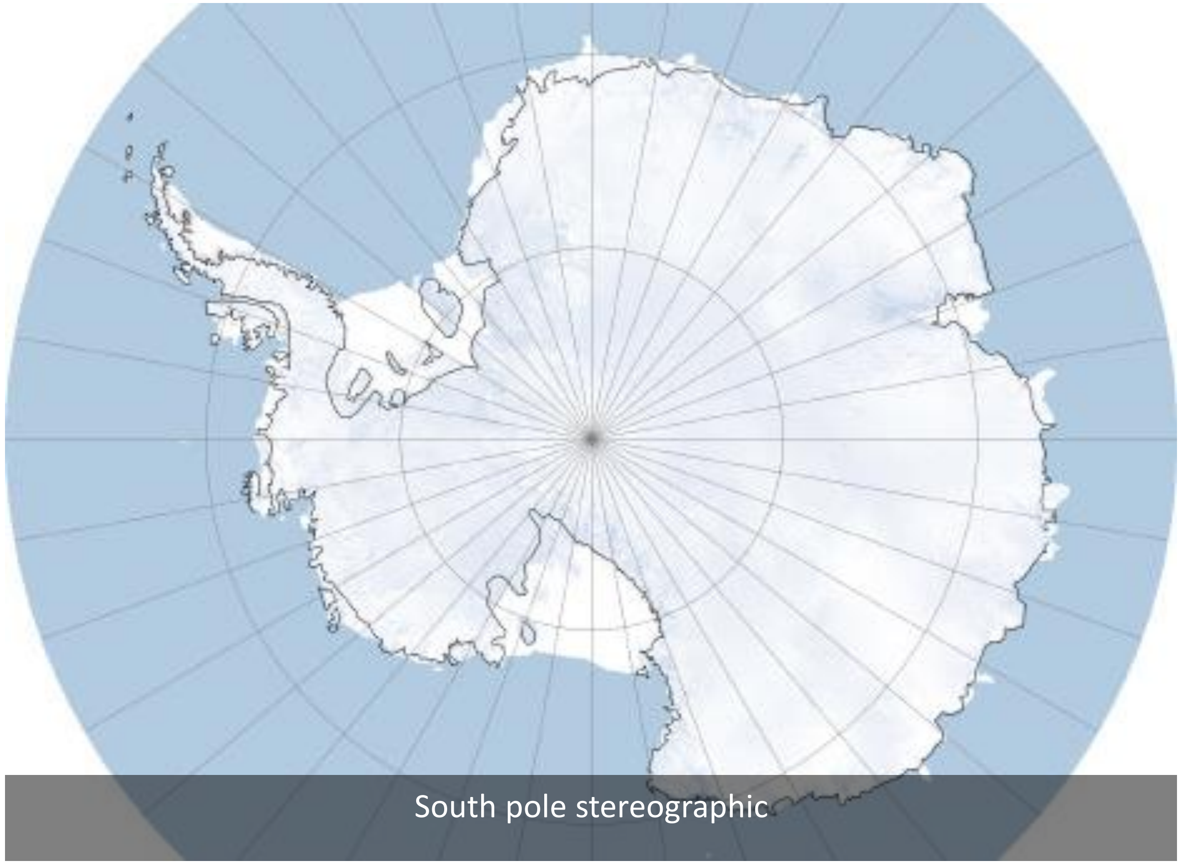
Orthographic (Azimuthal)

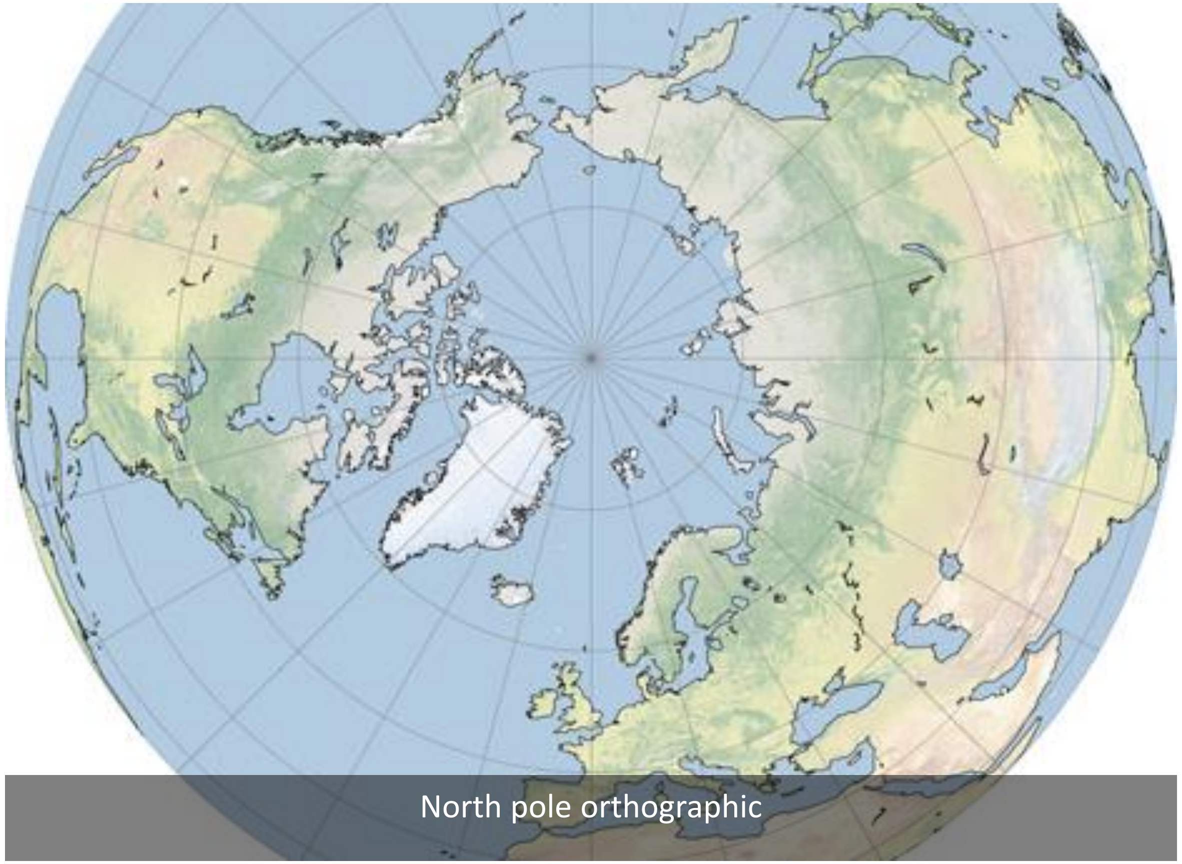


Stereographic (Azimuthal)



When would we want to use an Azimuthal projection?

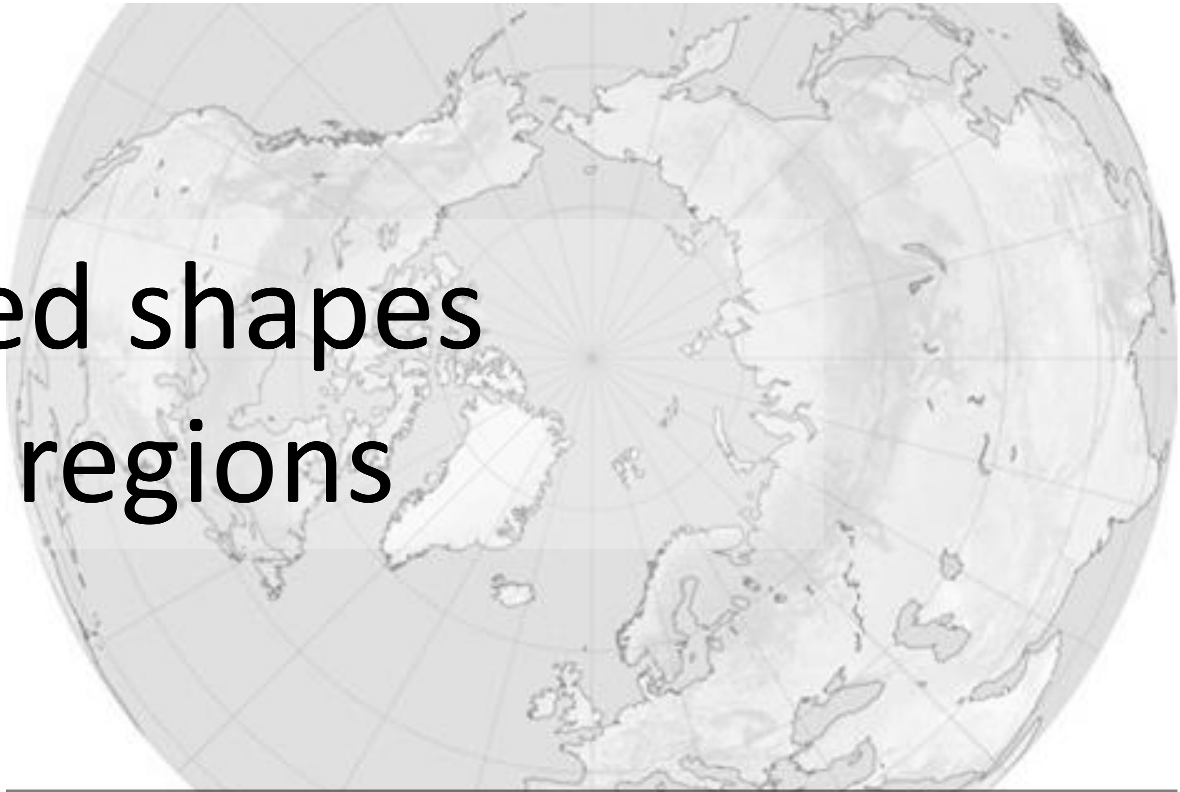

South pole stereographic


North pole orthographic

When would we want to use an Azimuthal projection?

- Rounded shapes
- Polar regions


South pole stereographic

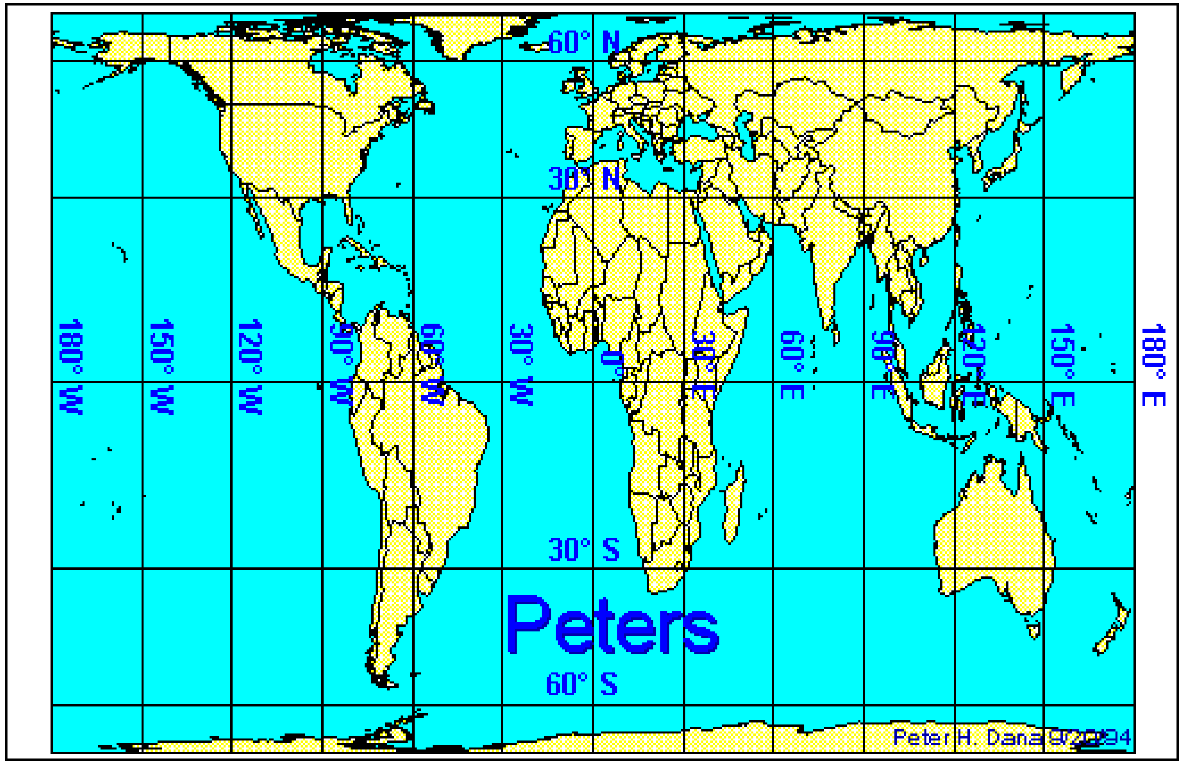

North pole orthographic

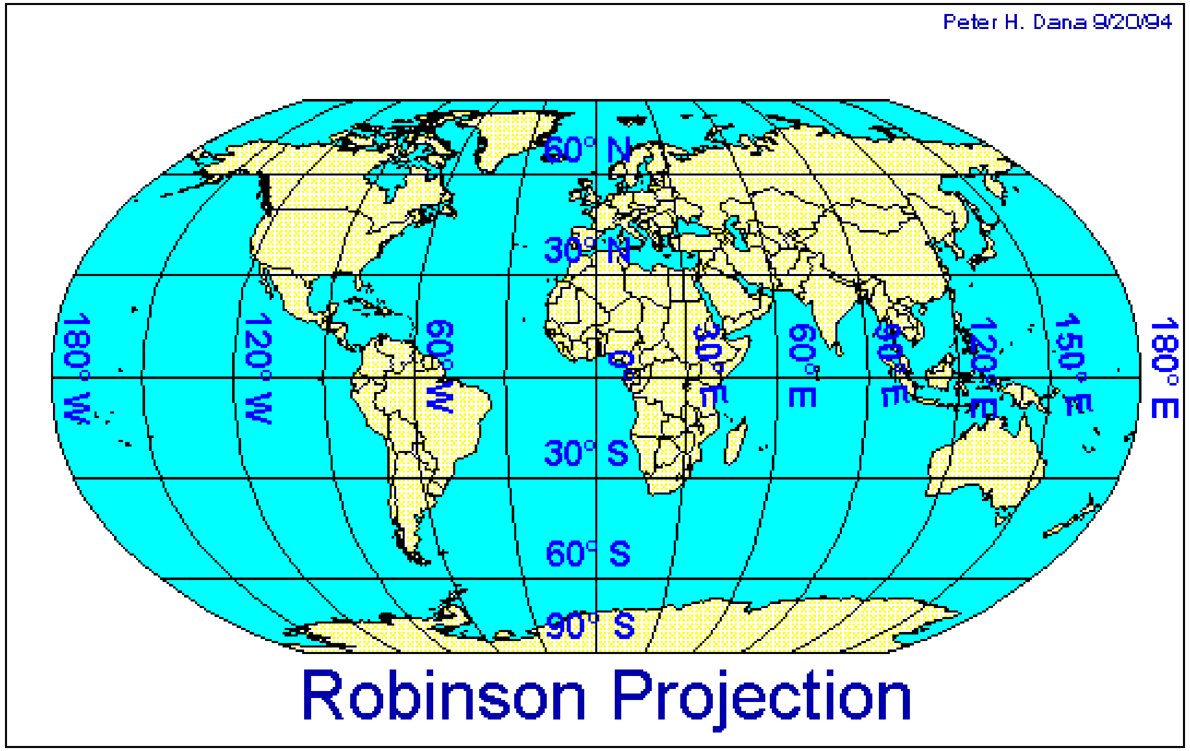
The Map Projection Process II

- Projecting GIS data from one map projection to another is accomplished via ***exact*** mathematical transformations.
- Vector data can be projected "on the fly" (in real time) and does not result in loss of information.
- ArcMap can display rasters reprojected on the fly, resulting in distorted cells, but no loss of information.
- Re-projecting raster data is computationally intensive and can result in loss of information.

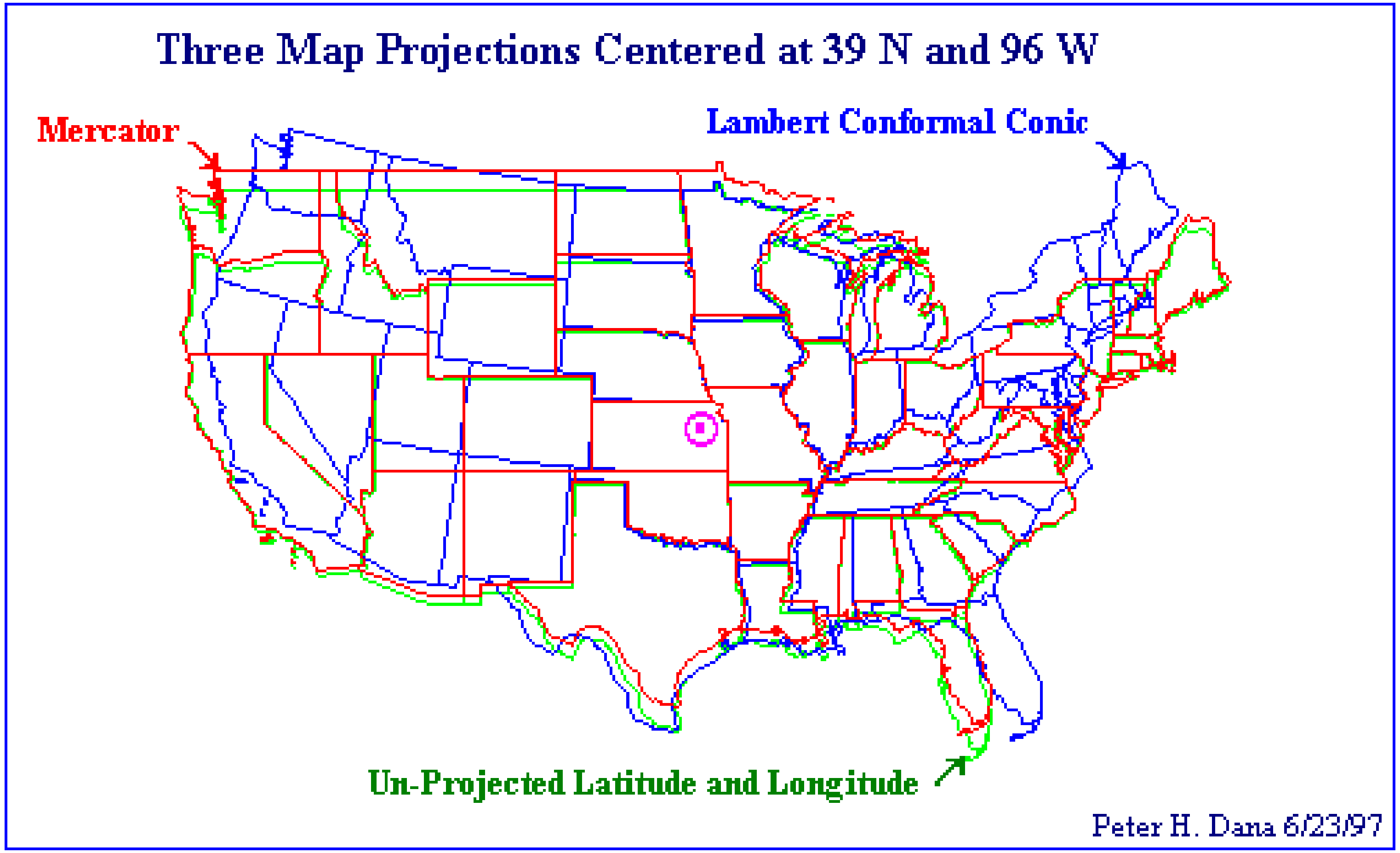
Why Map Projections Matter

They literally affect our *world view*.



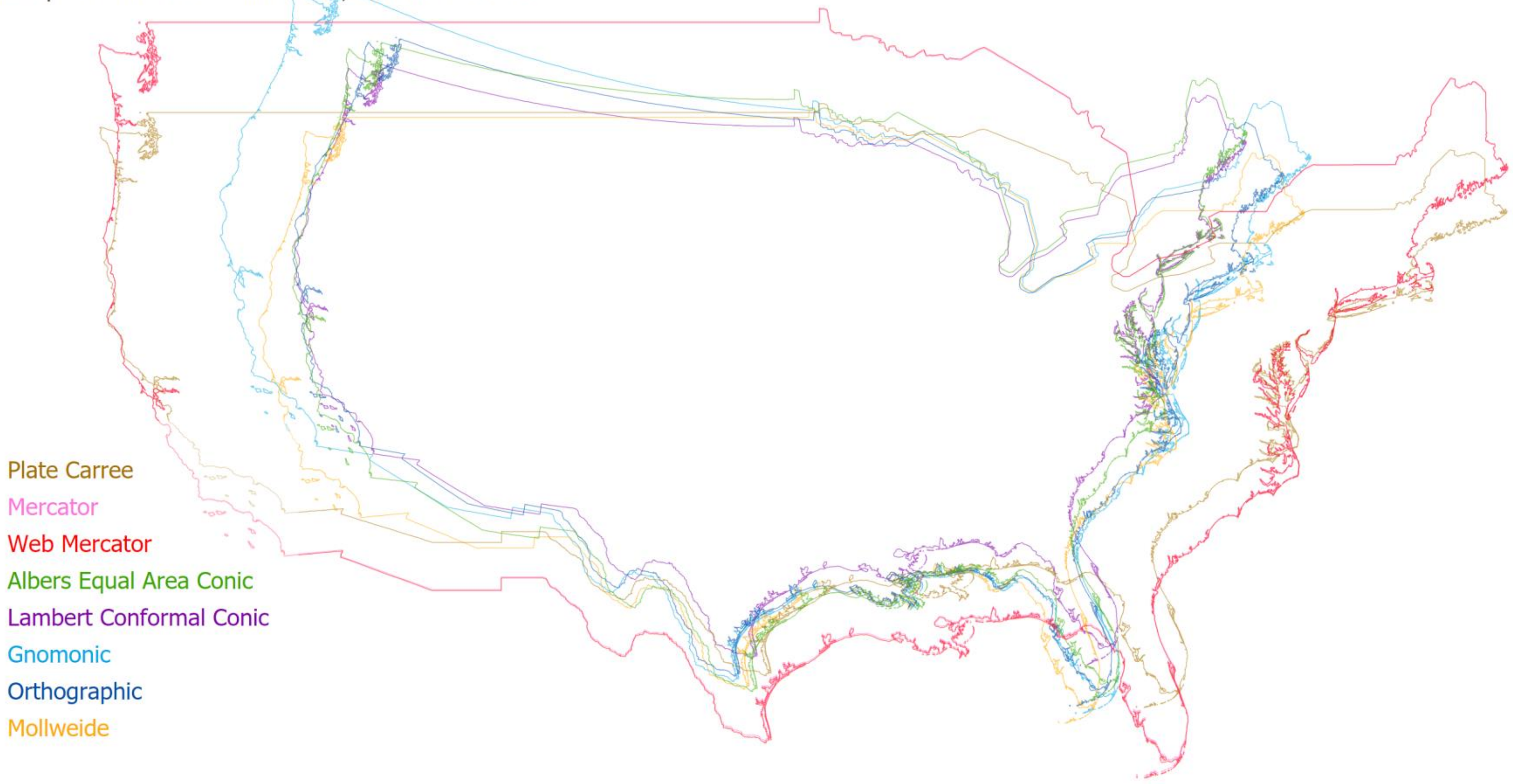


Or your *regional view*



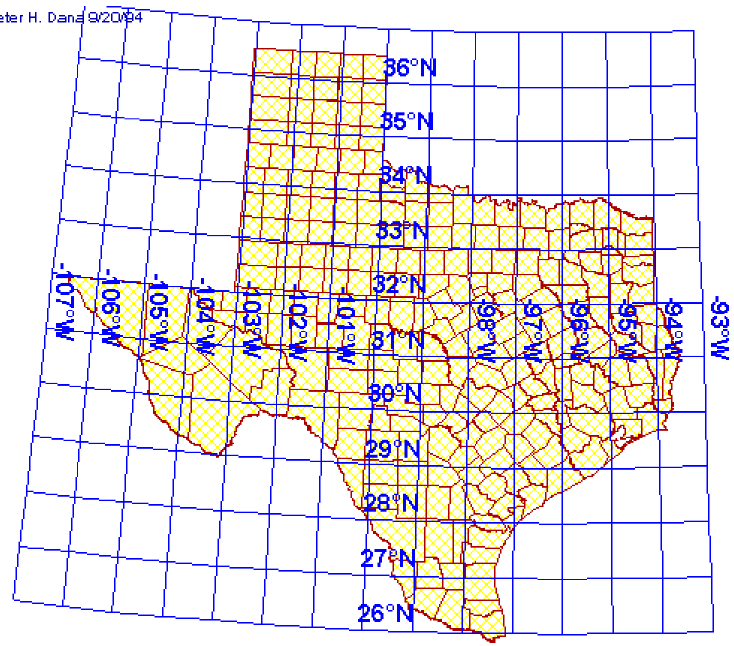
Continental USA in Eight Projections

All shapes drawn at the same scale, with the same center

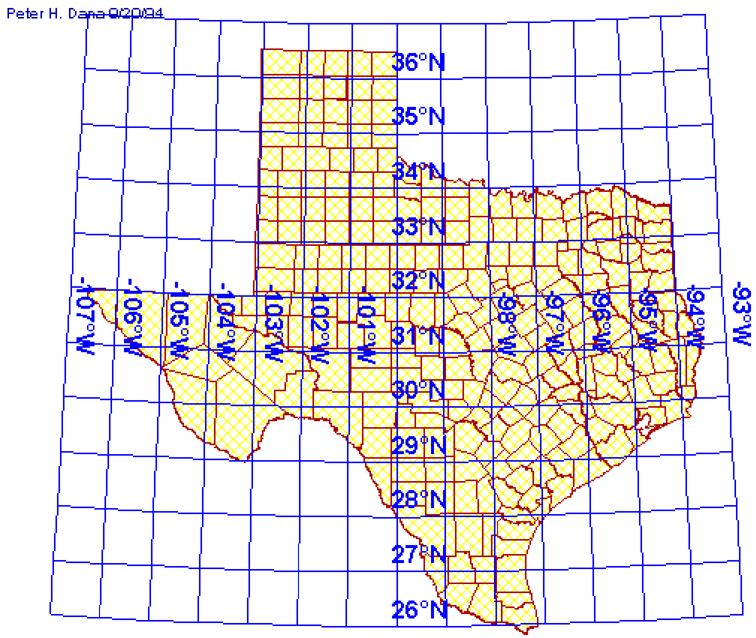


http://mjfoster83.github.io/projections/lib/img/eight-projections.png

Or if you live in a big state like Texas...Your Local View



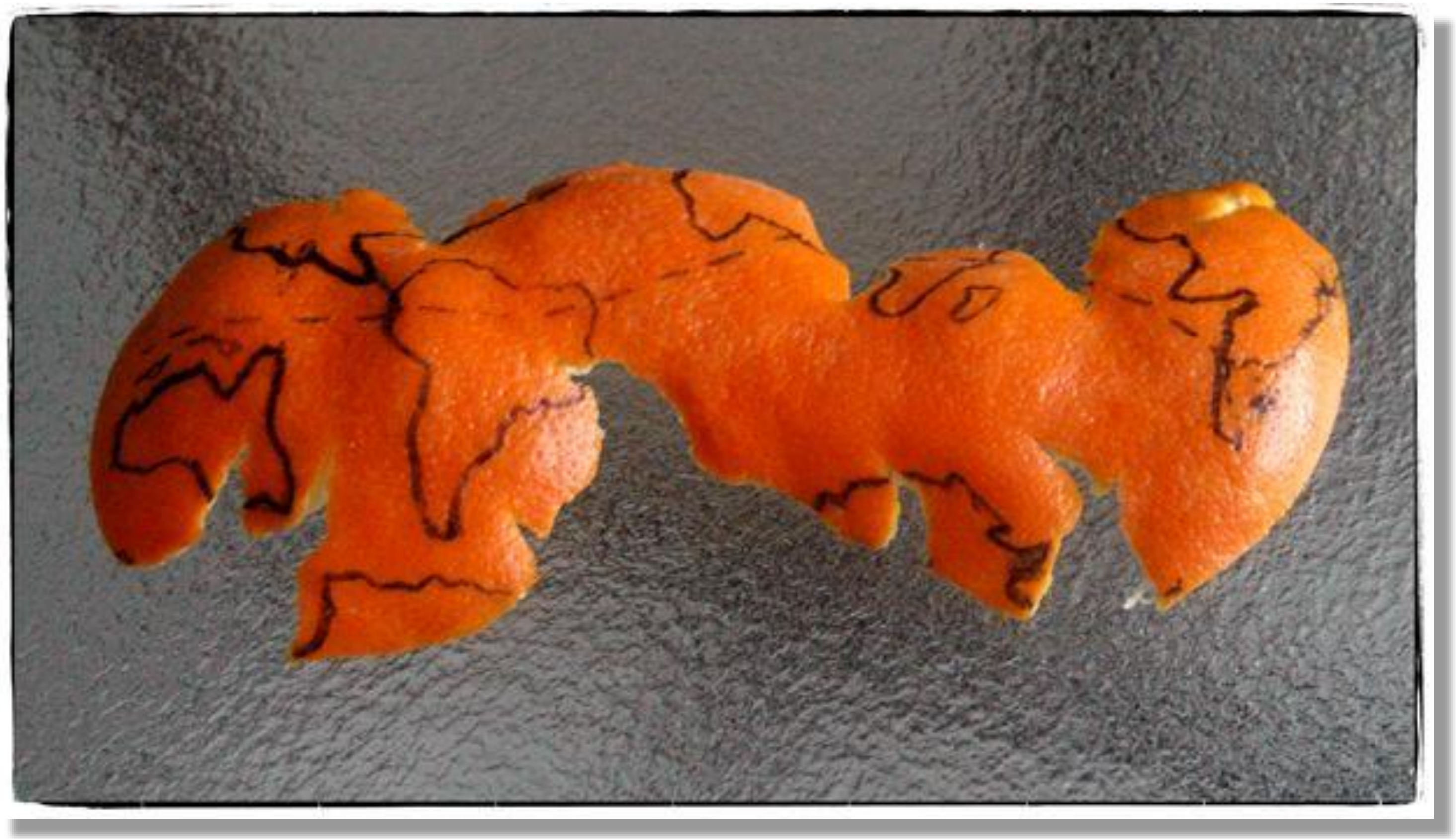
Lambert Conformal Conic (Cont. US)



Texas State-Wide Map Projection

Much Like Thermodynamics, You Can't Win

- When going from a 3-D sphere to a 2-D piece of paper it is inevitable that distortion will occur.
- To maintain one of the properties, you have to give up the others.
- Selection of a map projection means deciding what to save and what to give up.



The Classic Orange Peel

https://s-media-cache-ak0.pinimg.com/736x/2d/81/fc/2d81fcafacdc11ec04f34d1b1c587954.jpg

Reprojecting

- Read the metadata!
  - To use spatial data you need to know the projection.
- Combining data sets in different projections:
  - Bad idea.
  - You must re-project
- GIS software can help

ArcGIS can translate between projections

ArcGIS will reproject ‘on the fly’

- You can have multiple spatial layers with different projections
- The ArcMap document can be in a different projection from your data layers
- *As long as your projections are defined correctly, everything will be fine*

ArcGIS can translate between projections

UNLESS

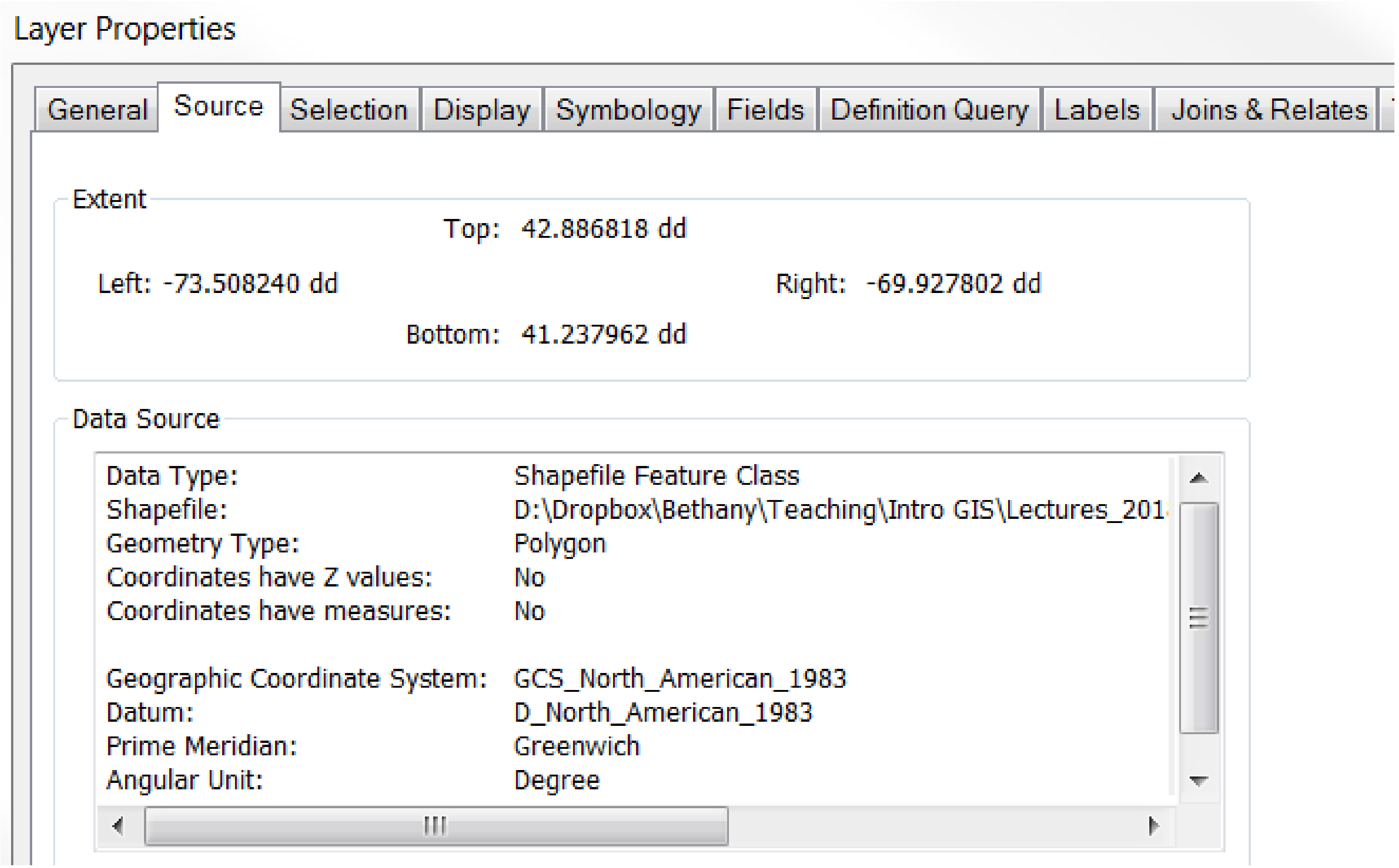
- You are using spatial data with different projections, *but those projections are not defined*

OR

- Your projection is *incorrectly* defined
  - *Someone's metadata is wrong in the internet!*

Need projection info about your data?

Use the source (tab)



Spatial Data Formats: Projections and Reversibility

Vector data: Vertices have explicit x- and y-coordinates.

- Transformations are reversible.

Raster data: Cell location is implicitly defined by corner coordinates, number of rows, number of columns.

- Transformations may be destructive: output rasters may have different number of rows and columns

Globe vs. Map

- Globes preserve:
  - Area
  - Shape
  - Distance
  - Direction

- Maps *may* preserve:
  - Area: equal area projections
  - Shape: conformal projections
  - Distance: equidistant projections
  - Direction: azimuthal preojections

The Four Classes of Maps

- There are four general classes of map. Each of these four types is designed to preserve one of the four major properties of a globe, but to accomplish this it is necessary to make accommodations in the other three…

- The art of selecting an appropriate map projection is determining which property of the globe is most important to preserve while striving to minimize distortions in the others for your area of interest

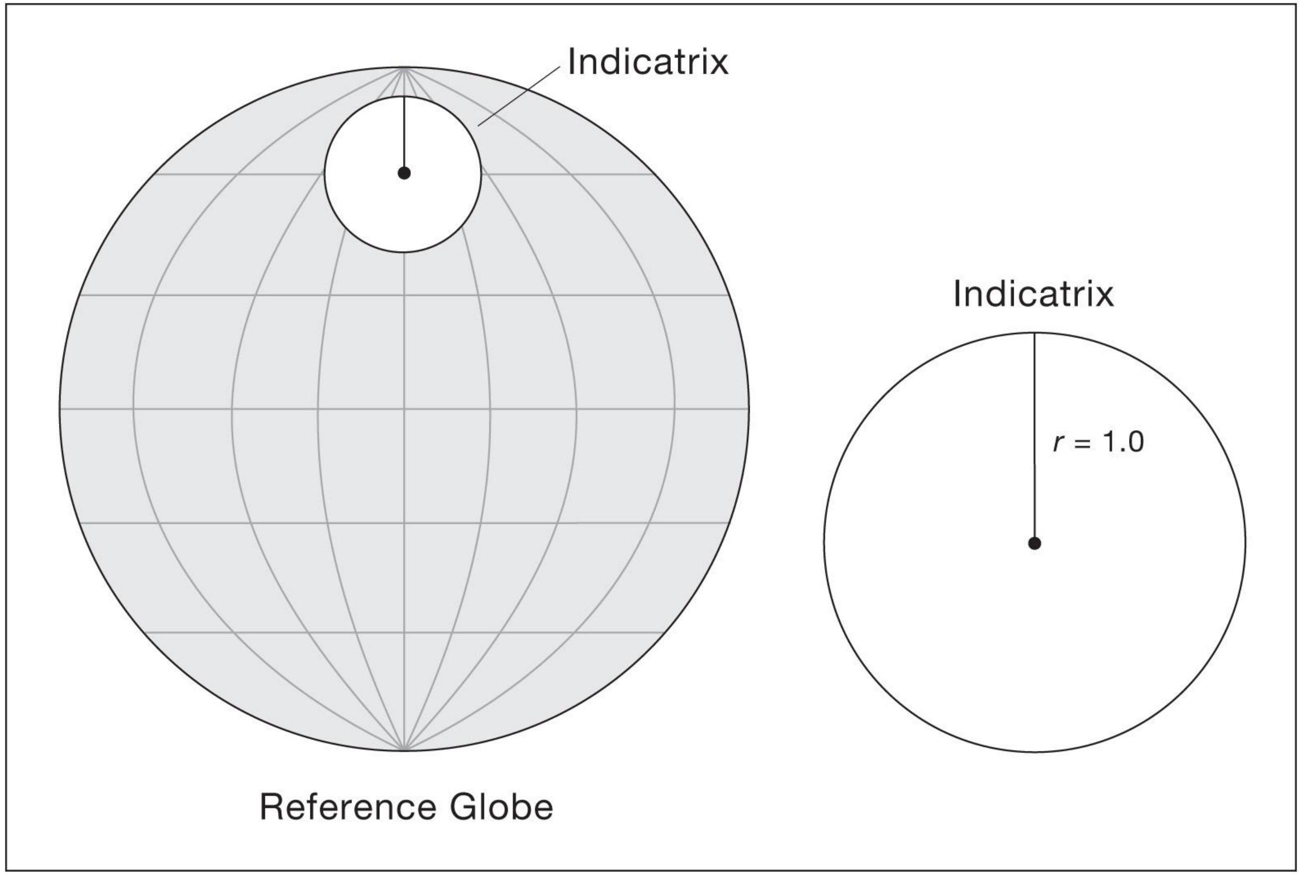
Map Classes: maps can preserve:

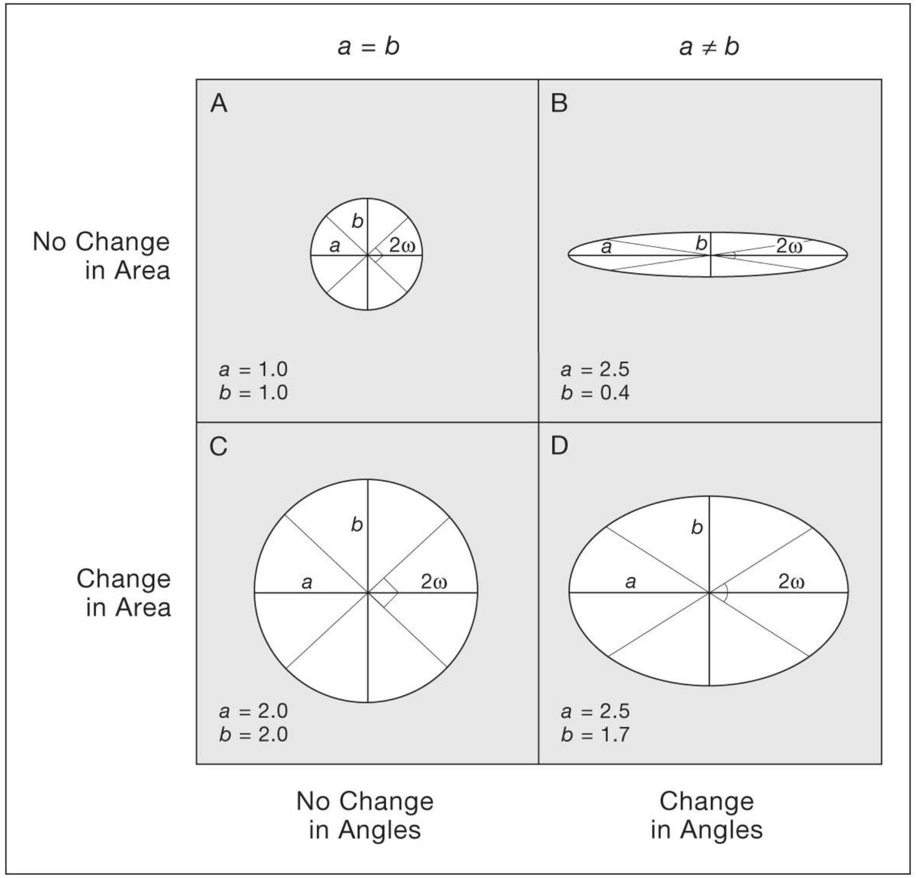
1. Size: equal-area

2. Distance: equidistant

3. Shape: conformal

4. Direction: azimuthal
   - Direction only true from central point

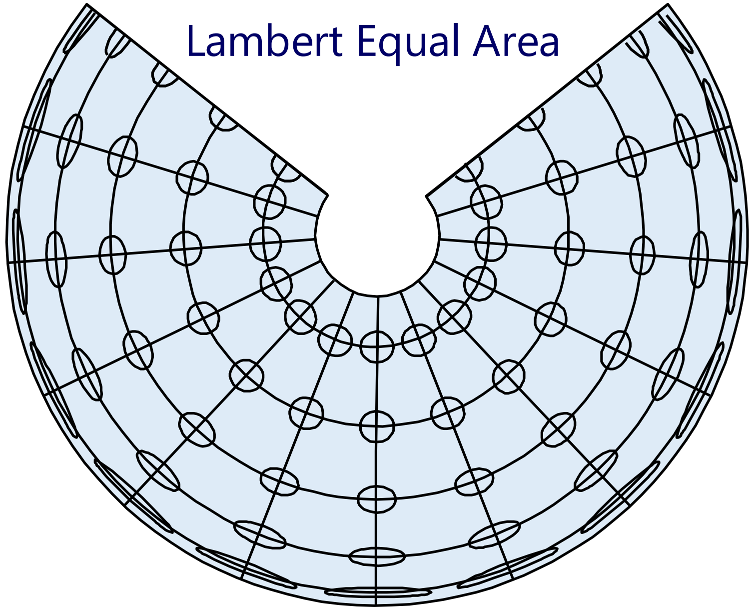


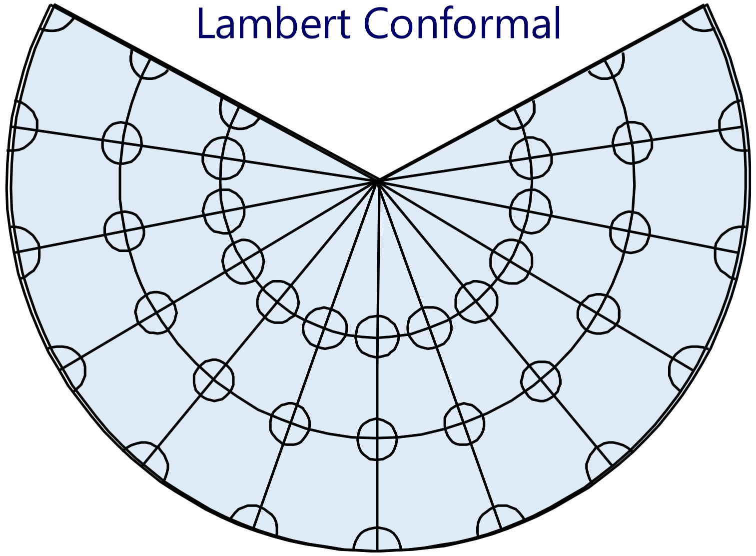


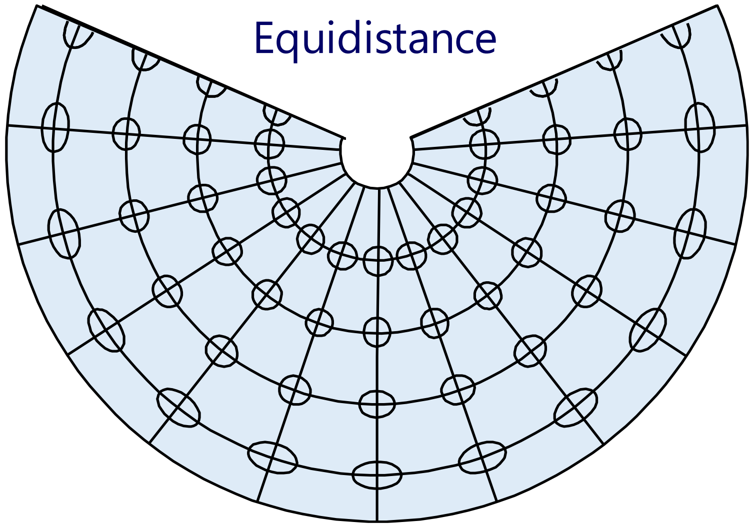
Tissot Indicatrix

Projections and Tissot's Indicatrix

- Source: Thomas Rabenhorst

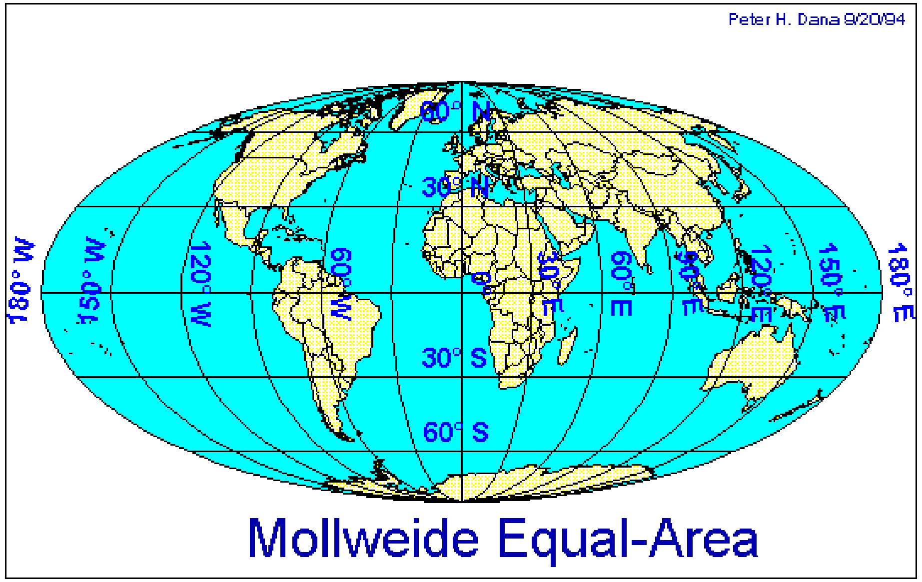


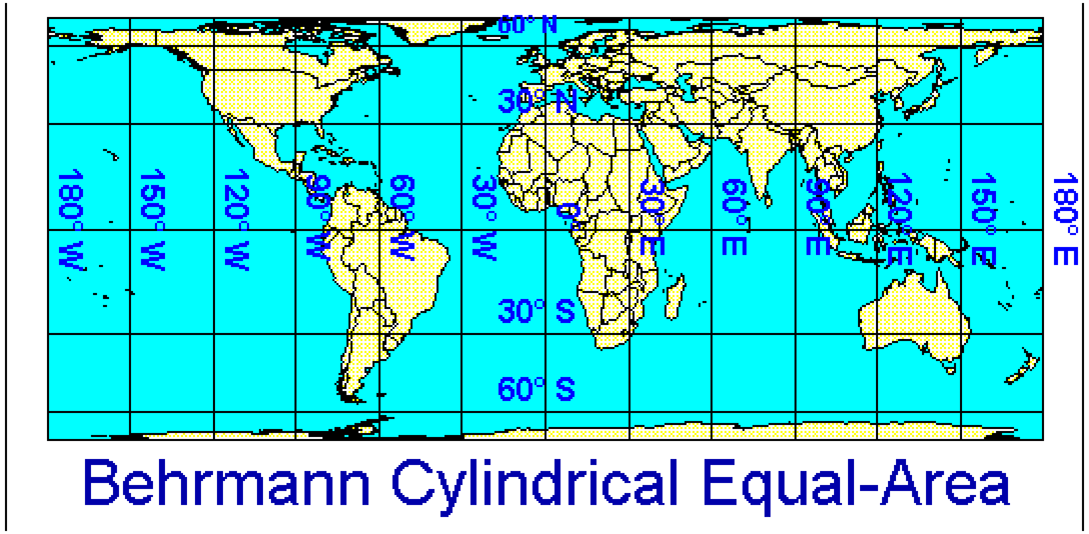




Equal Area

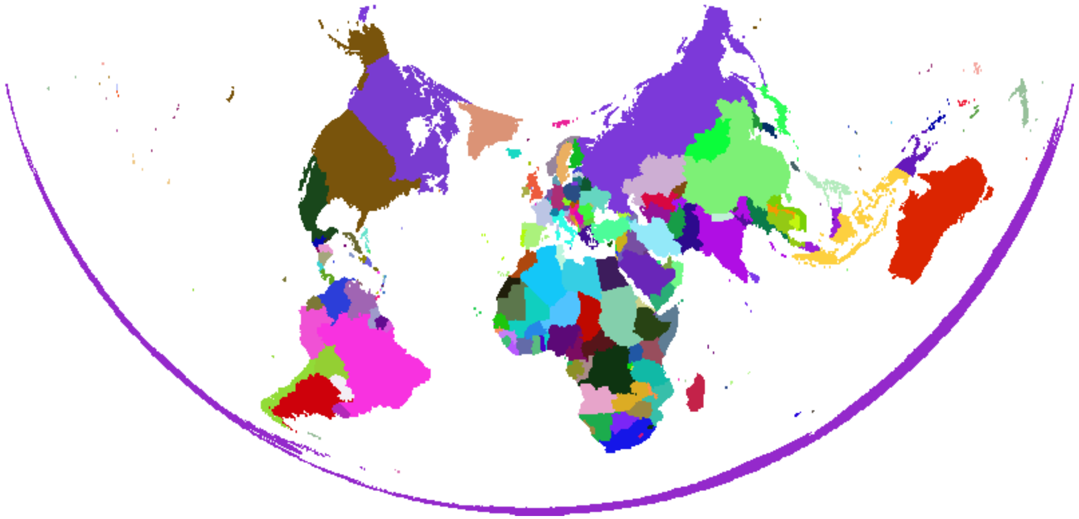
Areas are preserved at the expense of other properties.



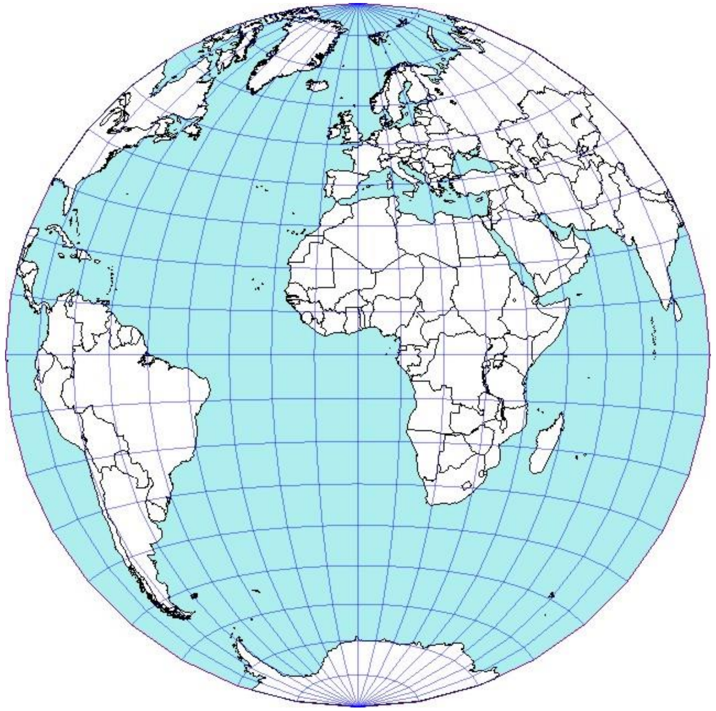


Area Preserving (Equal Area)

Advantages	Disadvantages
• Equal area projections are best employed to show spatial distributions and relative sizes of spatial features, such as political units, population,land use and land cover, soils, wetlands,wildlife habitats, and natural resource inventories.	• Spatial features on the maps will inevitably be distorted in shapes, distances, and occasionally, directions.



Albers Equal-Area Conic Projection



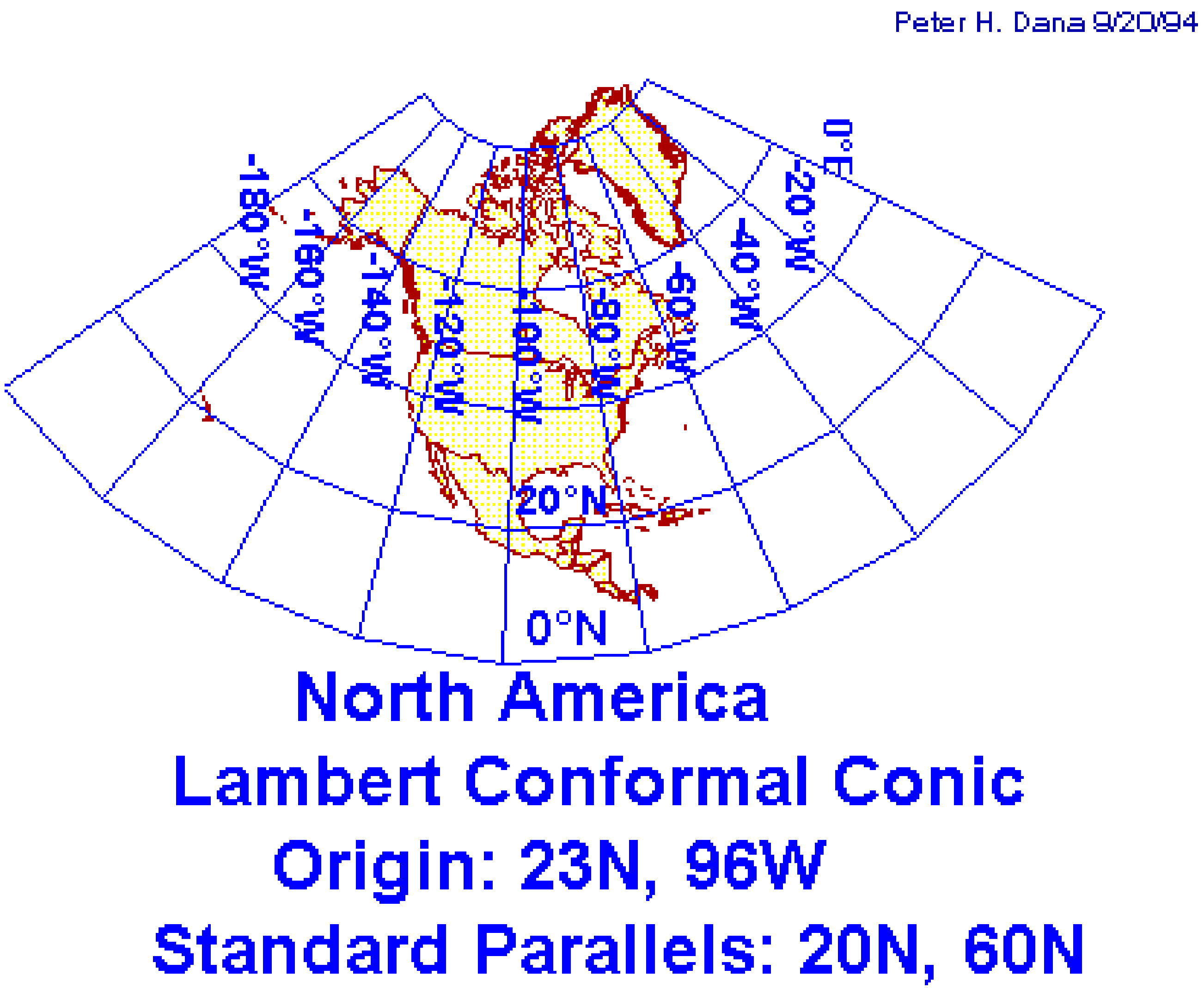
Lambert Azimuthal Equal-Area Projection

Class	*Conic*
Aspect	*Normal*
Property	*Equal-Area*

Class	*Azimuthal*
Aspect	*Normal*
Property	*Equal-Area*

Conformal

- Shape (of small areas) are preserved.
- Preserves local angles.
- Ideal for navigation.



Shape Preserving (Conformal)

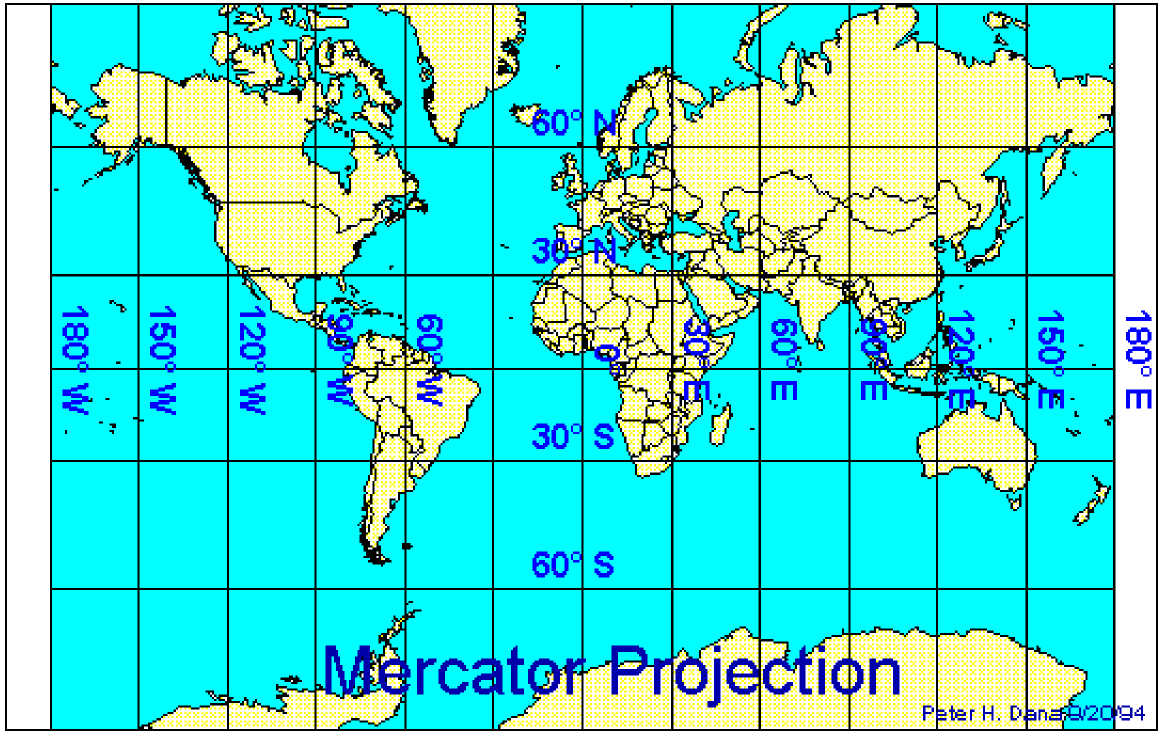
ADVANTAGES

- Relative local angles about every point on the map are shown corectly.
- Important for topographic mapping and navigation purposes

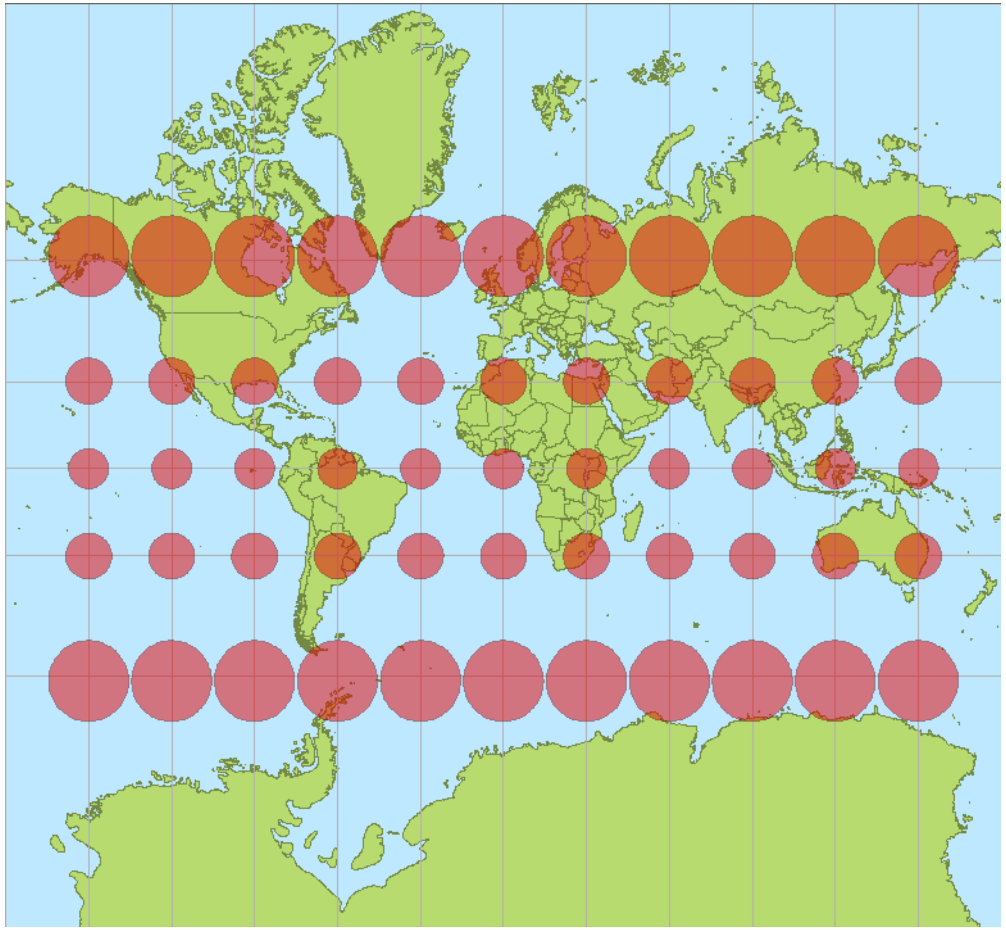
DISADVANTAGES

- The need to retain shape inevitably distorts both area and distance

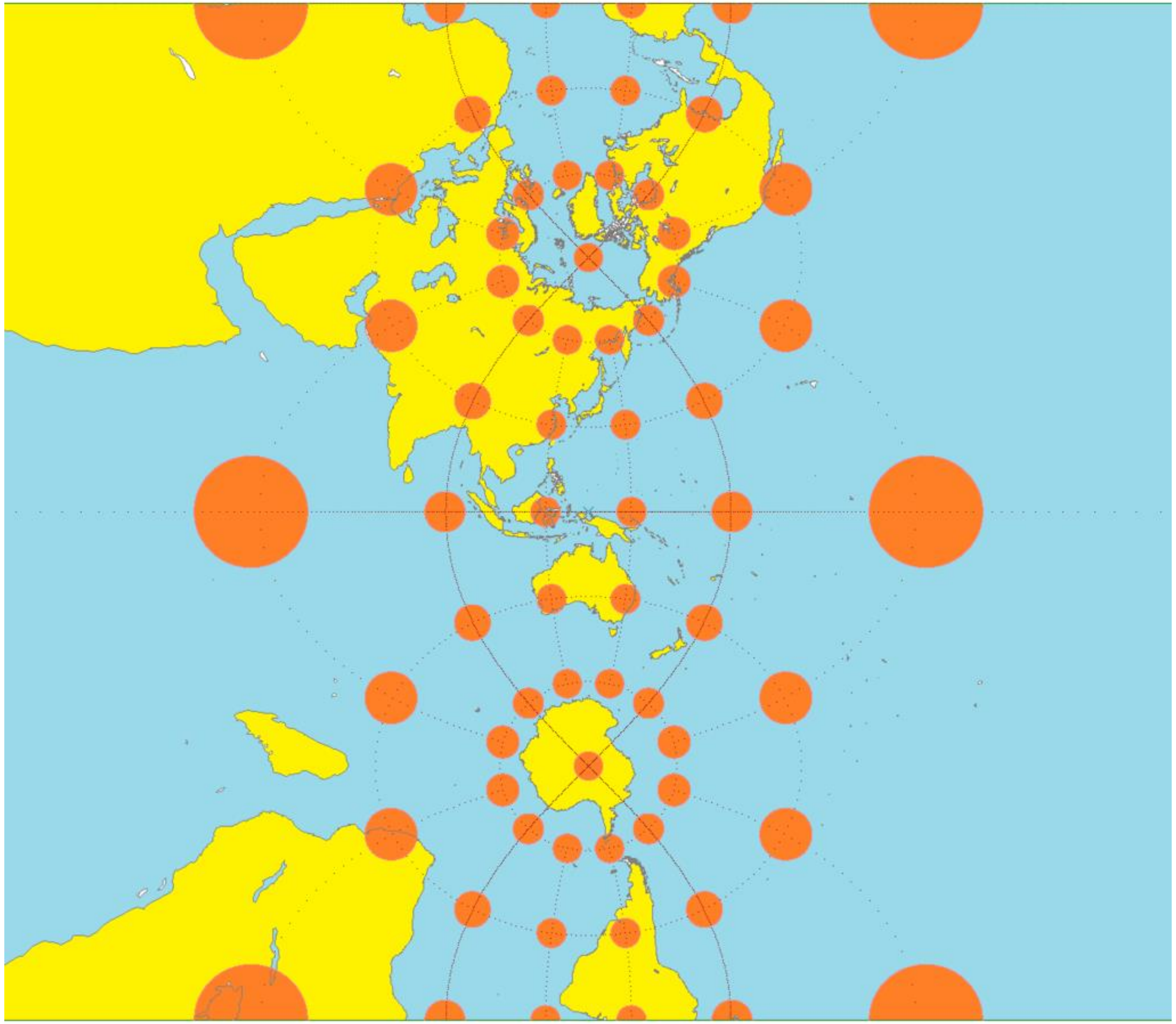
Ex: Mercator Projection



Class	*Cylindrical*
Aspect	*Normal*
Property	*Conformal*

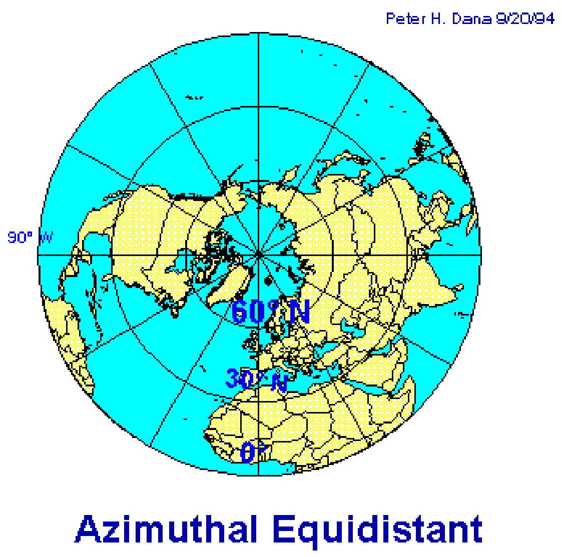


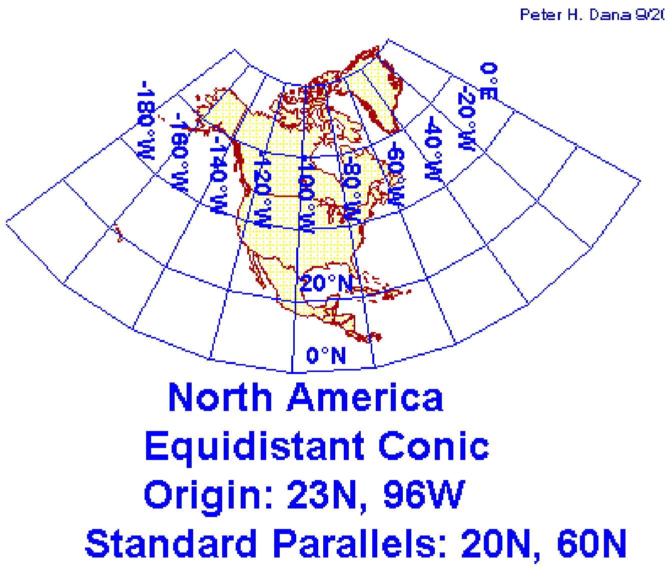
Class	*Cylindrical*
Aspect	*Transverse*
Property	*Conformal*



Equidistant

- Distance along designated great circles are true; or:
- Distances from one point to all others is true.





Distance Preserving (Equidistant)

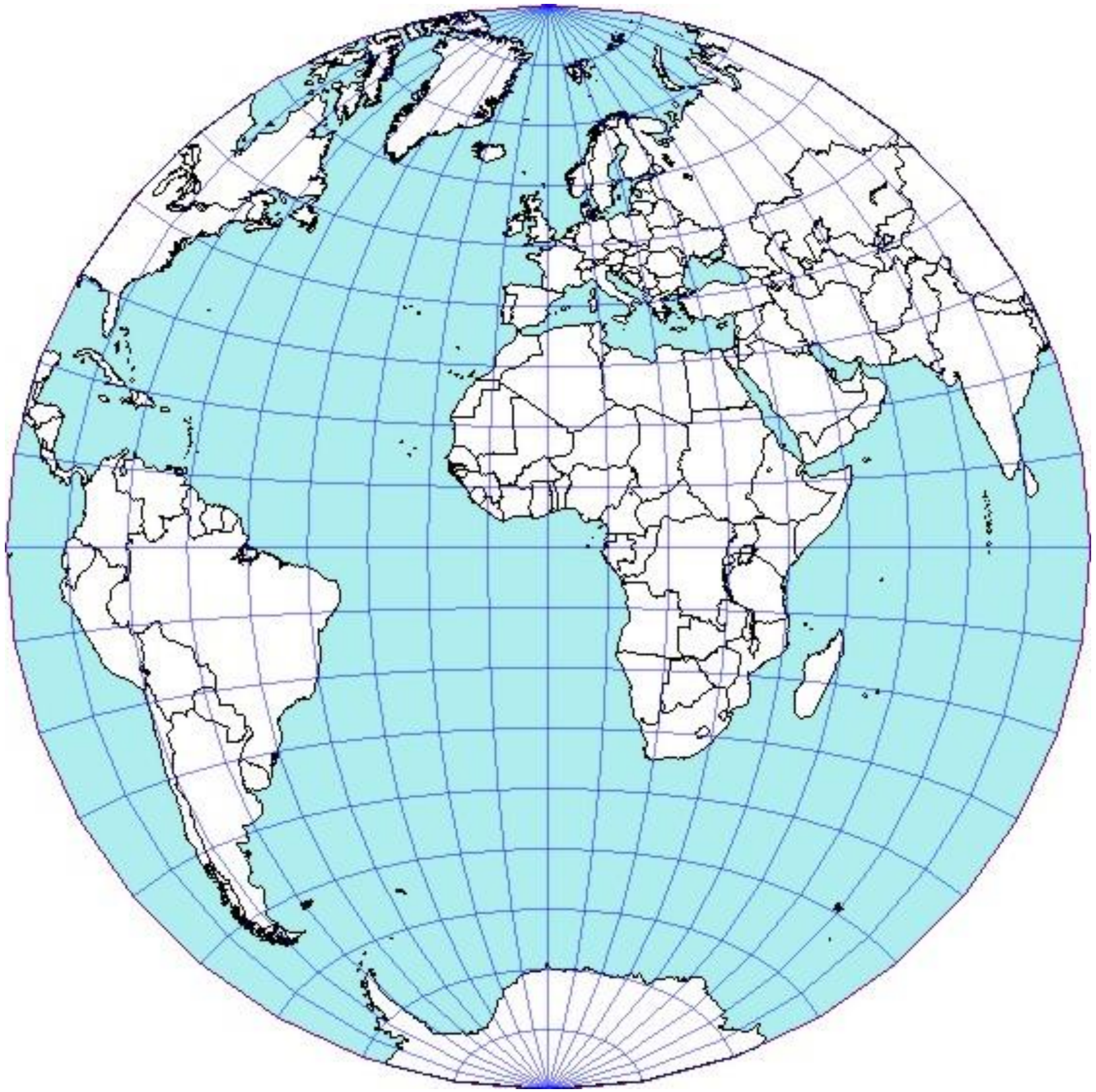
ADVANTAGES

- Equidistance is a useful compromise between the conformal and equal-area projections because the area scale of an equidistant map projection increases more slowly than that of a conformal map projection. As a result, the equidistant map projection is used more often in atlas maps.

DISADVANTAGES

- The property of equidistance is very sensitive to scale change.
- All measurements made away from the lines of true scale are subject to distance distortion due to changing scales.

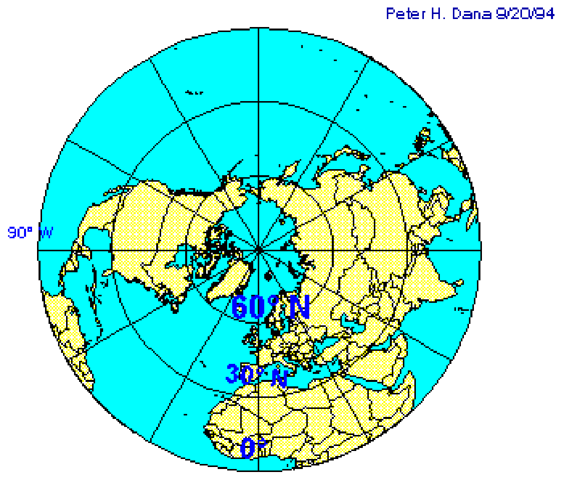
Class	*Azimuthal*
Aspect	*Normal*
Property	*Equidistant*



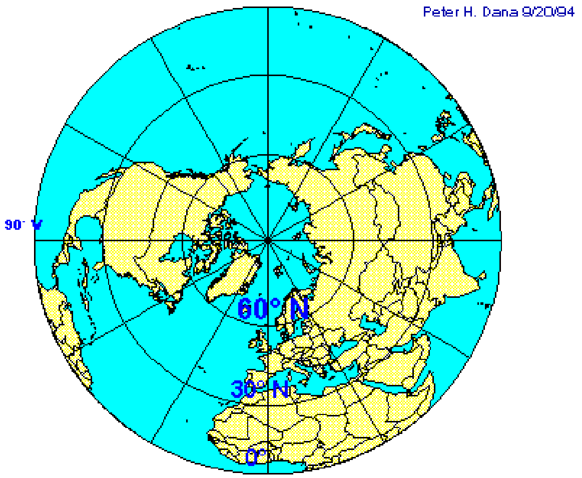
Source

Azimuthal

- True direction is shown from one central point
- to all other points



Azimuthal Equidistant



Lambert Azimuthal Equal Area

Choosing a Map Projection

- The selection of a map projection has to be made on the basis of:

  - Shape and size of the area
  - Purpose of the map
  - Position of the area

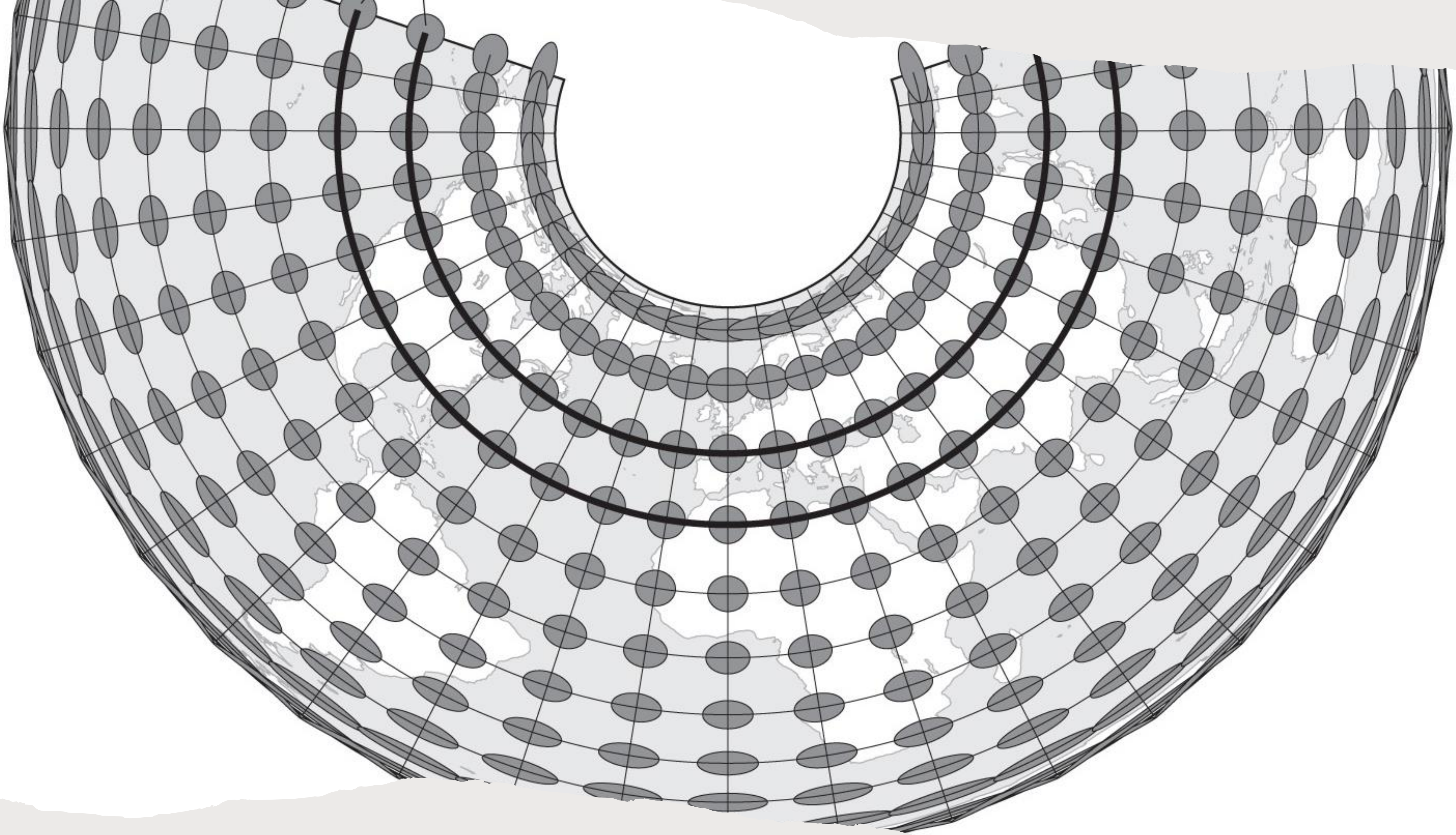
Purpose of the Map

- Conformal
  - maps which require measuring angles (*aeronautical charts, topographic maps*)
- Equivalent
  - maps which require measuring areas (*distribution maps*)
- Equidistance
  - maps which require reasonable area and angle distortions *(several thematic maps)*

Snyder’s map projection guideline

TABLE 9.1 Snyder’s map projection guideline showing projections for mapping the world

Region Mapped	*Property*	*Characteristic*	*Named Projection*
World	Conformal	Constant scale along Equator	Mercator
		Constant scale along a meridian	Transverse Mercator
		Constant scale along an oblique great circle	Oblique Mercator
		No constant scale anywhere on the map	Lagrange August Eisenlohr
	Equivalent	Noninterrupted	Mollweide
			Eckert IV & VI McBryde or McBryde–Thomas Boggs Eumorphic Sinusoidal Other miscellaneous pseudocylindricals
			Hammer (a modified azimuthal)
		Interrupted	Any of the above except Hammer Goode’s Homolosine
		Oblique aspect	Briesemeister Oblique Mollweide
	Equidistant	Centered on a pole	Polar azimuthal equidistant
		Centered on a city	Oblique azimuthal equidistant
	Straight rhumb lines		Mercator
	Compromise distortion		Miller cylindrical Robinson pseudocylindrical



Snyder’s map projection guideline

TABLE 9.2 Snyder’s projection selection guideline showing planar projections for mapping a hemisphere

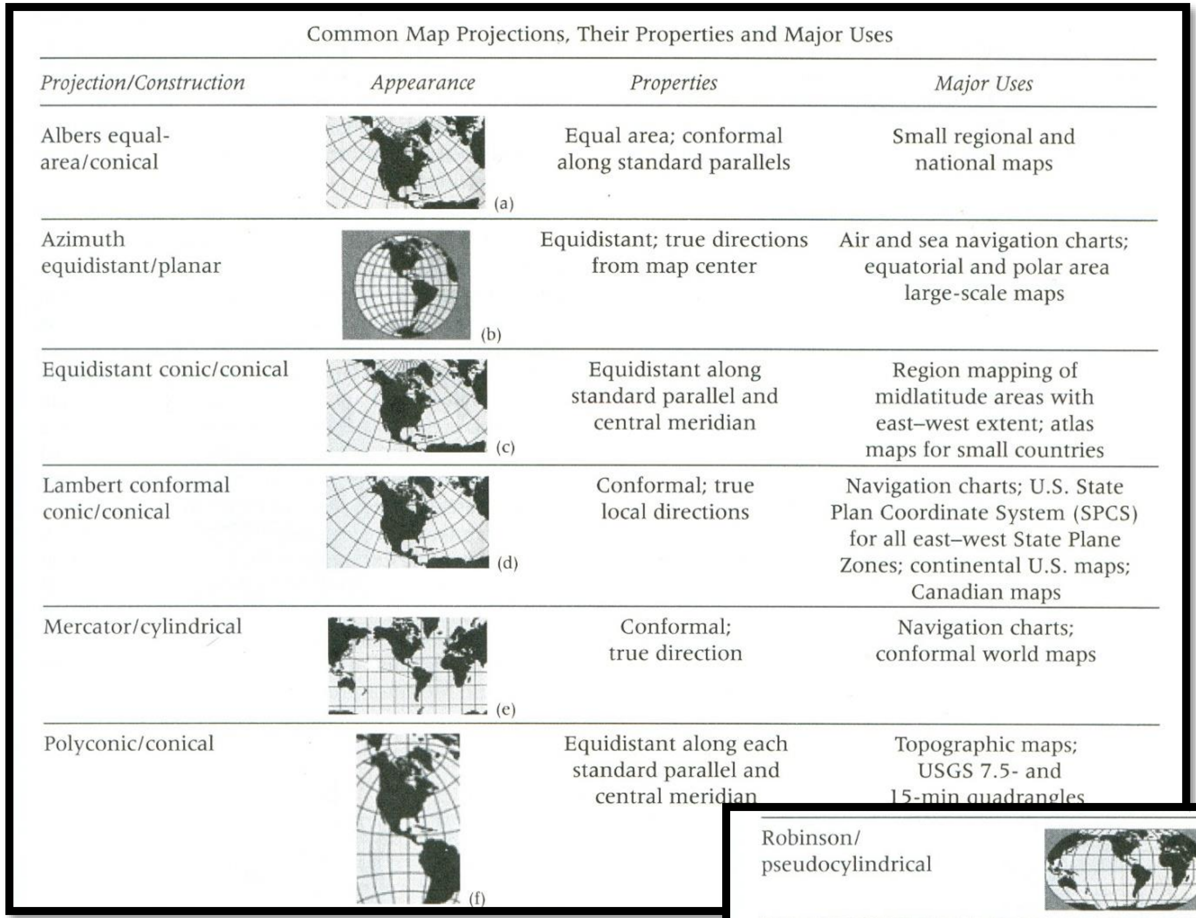
Region Mapped	*Property*	*Named Projection*
Hemisphere	Conformal	Stereographic conformal
	Equivalent	Lambert azimuthal equivalent
	Equidistant	Azimuthal equidistant
	Global look	Orthographic

Snyder’s map projection guideline

TABLE 9.3 A portion of Snyder’s map projection guideline, showing projections for mapping a continent, ocean, or smaller region

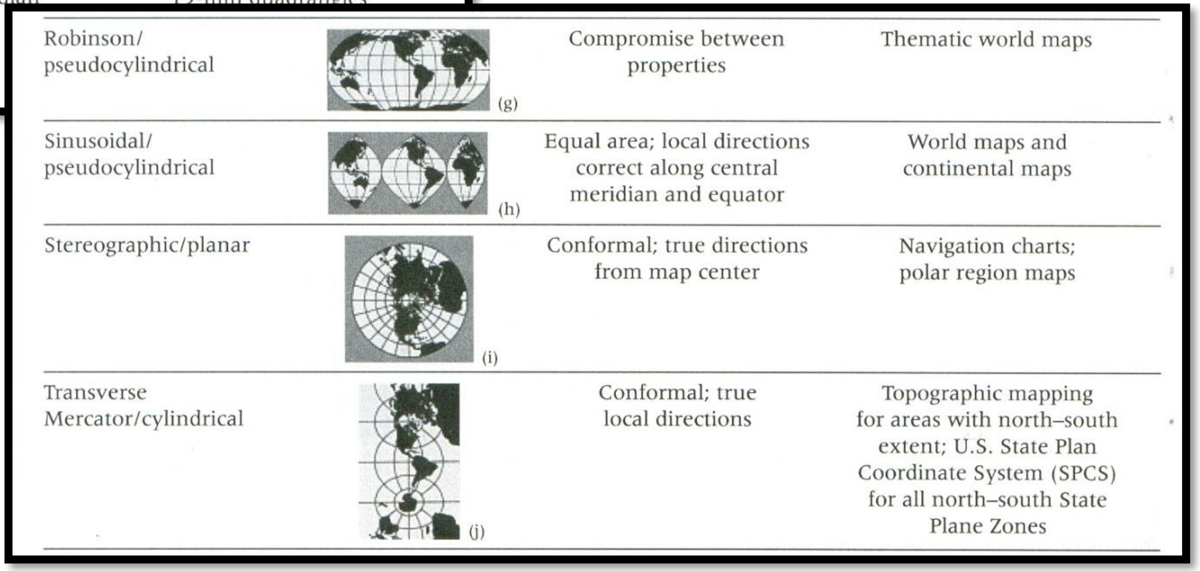
Region Mapped	*Directional Extent*	*Location*	*Property*	*Named Projection*
Continent, ocean, or smaller region	East–West	Along the Equator	Conformal	Mercator
			Equivalent	Cylindrical equivalent
		Away from the Equator	Conformal	Lambert conformal conic
			Equivalent	Albers equivalent conic
	North–South	Aligned anywhere along a meridian	Conformal	Transverse Mercator
			Equivalent	Transverse cylindrical equivalent
	Oblique	Anywhere	Conformal	Oblique Mercator
			Equivalent	Oblique cylindrical equivalent
	Equal extent	Polar, Equatorial, or Oblique	Conformal	Stereographic
			Equivalent	Lambert azimuthal equivalent

Common Map Projections, Their Properties and Major Uses



Common Map Projections, Their Properties and Major Uses

Projection/Construction	*Appearance*	*Properties*	*Major Uses*
Albers equal-area/conical	(a)	Equal area; conformal along standard parallels	Small regional and national maps
Azimuth equidistant/planar	(b)	Equidistant; true directions from map center	Air and sea navigation charts; equatorial and polar area large-scale maps
Equidistant conic/conical	(c)	Equidistant along standard parallel and central meridian	Region mapping of midlatitude areas with east–west extent; atlas maps for small countries
Lambert conformal conic/conical	(d)	Conformal; true local directions	Navigation charts; U.S. State Plan Coordinate System (SPCS) for all east–west State Plane Zones; continental U.S. maps; Canadian maps
Mercator/cylindrical	(e)	Conformal; true direction	Navigation charts; conformal world maps
Polyconic/conical	(f)	Equidistant along each standard parallel and central meridian	Topographic maps; USGS 7.5- and 15-min quadrangles



Robinson/pseudocylindrical	(g)	Compromise between properties	Thematic world maps
Sinusoidal/pseudocylindrical	(h)	Equal area; local directions correct along central meridian and equator	World maps and continental maps
Stereographic/planar	(i)	Conformal; true directions from map center	Navigation charts; polar region maps
Transverse Mercator/cylindrical	(j)	Conformal; true local directions	Topographic mapping for areas with north–south extent; U.S. State Plan Coordinate System (SPCS) for all north–south State Plane Zones

Summary

- Selection of a projection could be very confusing for a novice cartographer – there are good guidelines with a logical hierarchy (Snyder)
- Objective should be to keep distortion minimum
- Amount of distortion can be kept small by aligning the geographic area under the consideration with the standard lines or by positioning the map’s center with the standard point
- The size of the area to be map is directly linked to the importance of distortion
- The map projection has an influence on overall map design

Projection systems used in the world*

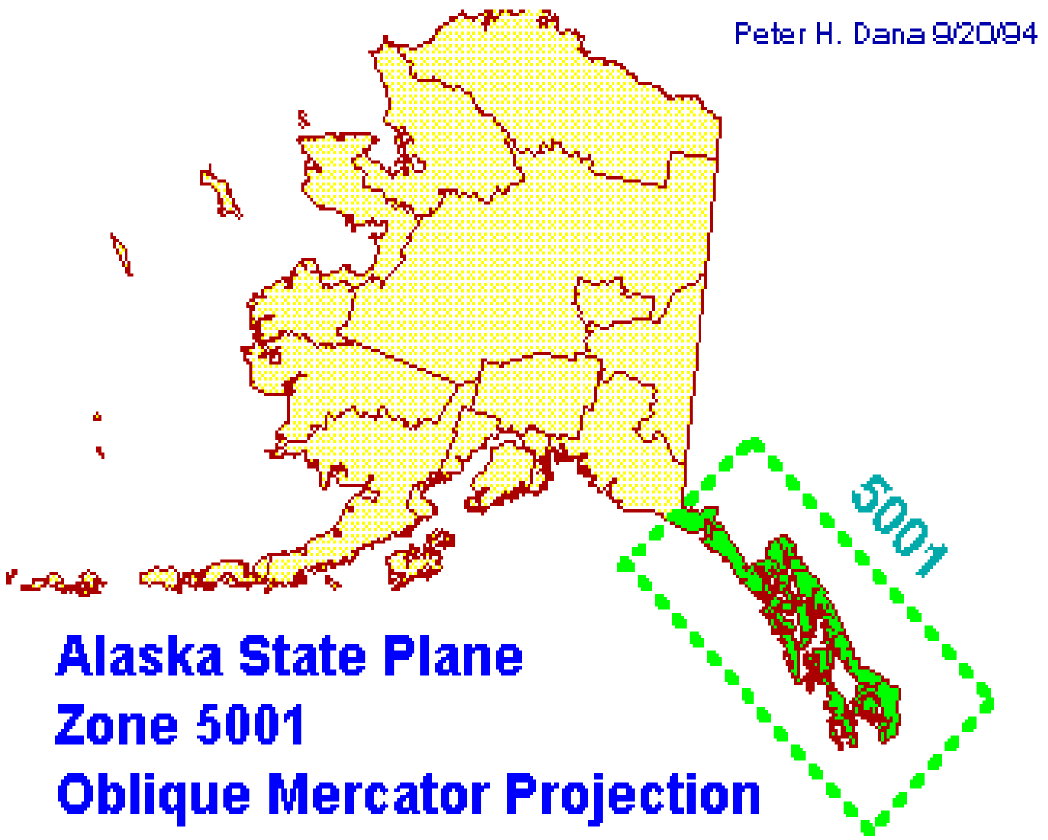
Projection	Areas
UTM	42 %
TM (Gauss-Kruger)	37 %
Polyconic	10 %
Lambert Conformal Conical	5 %
Others	6 %

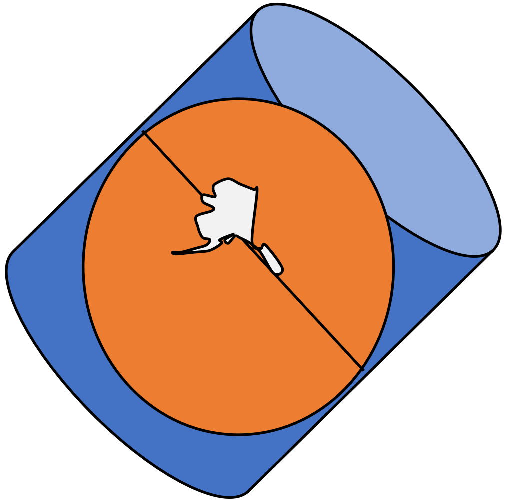
** for Topographic mapping*

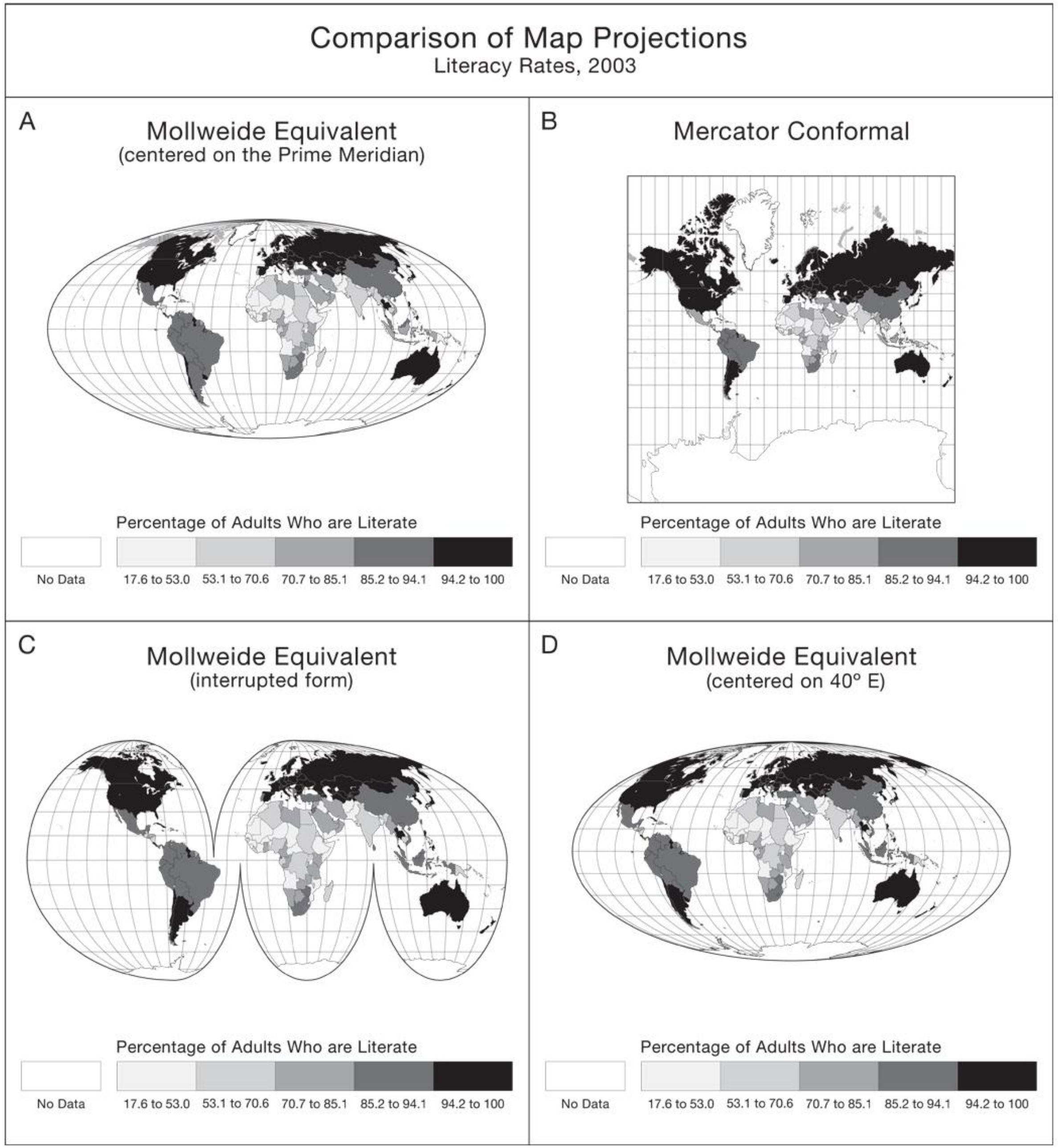
UTM

- The UTM projection is designed to cover the world, excluding the Arctic and Antarctic regions. To keep *scale distortions* within acceptable limits, 60 narrow, longitudinal zones of six degrees longitude in width are defined and are numbered from 1 to 60.

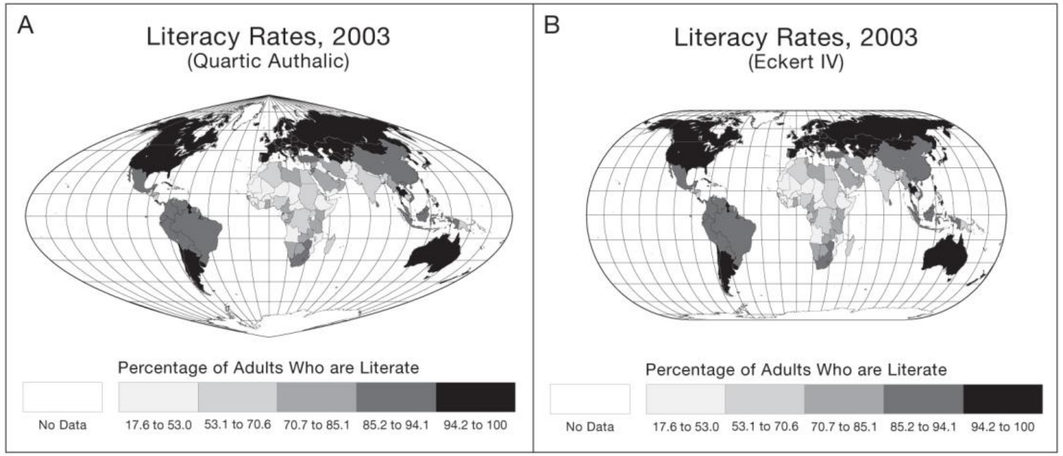
Position of the Area







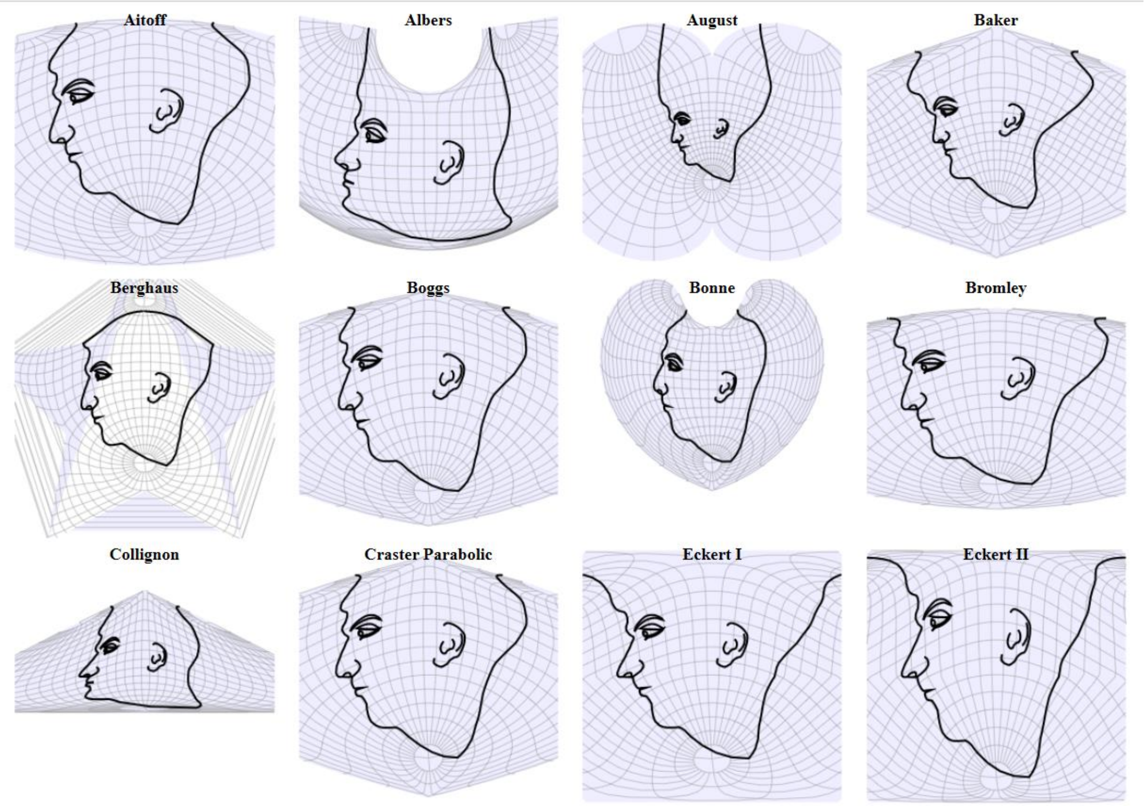
Comparison of Map Projections
Literacy Rates, 2003
A
Mollweide Equivalent
(centered on the Prime Meridian)
Percentage of Adults Who are Literate
No Data
17.6 to 53.0
53.1 to 70.6
70.7 to 85.1
85.2 to 94.1
94.2 to 100
B
Mercator Conformal
Percentage of Adults Who are Literate
No Data
17.6 to 53.0
53.1 to 70.6
70.7 to 85.1
85.2 to 94.1
94.2 to 100
C
Mollweide Equivalent
(interrupted form)
Percentage of Adults Who are Literate
No Data
17.6 to 53.0
53.1 to 70.6
70.7 to 85.1
85.2 to 94.1
94.2 to 100
D
Mollweide Equivalent
(centered on 40° E)
Percentage of Adults Who are Literate
No Data
17.6 to 53.0
53.1 to 70.6
70.7 to 85.1
85.2 to 94.1
94.2 to 100

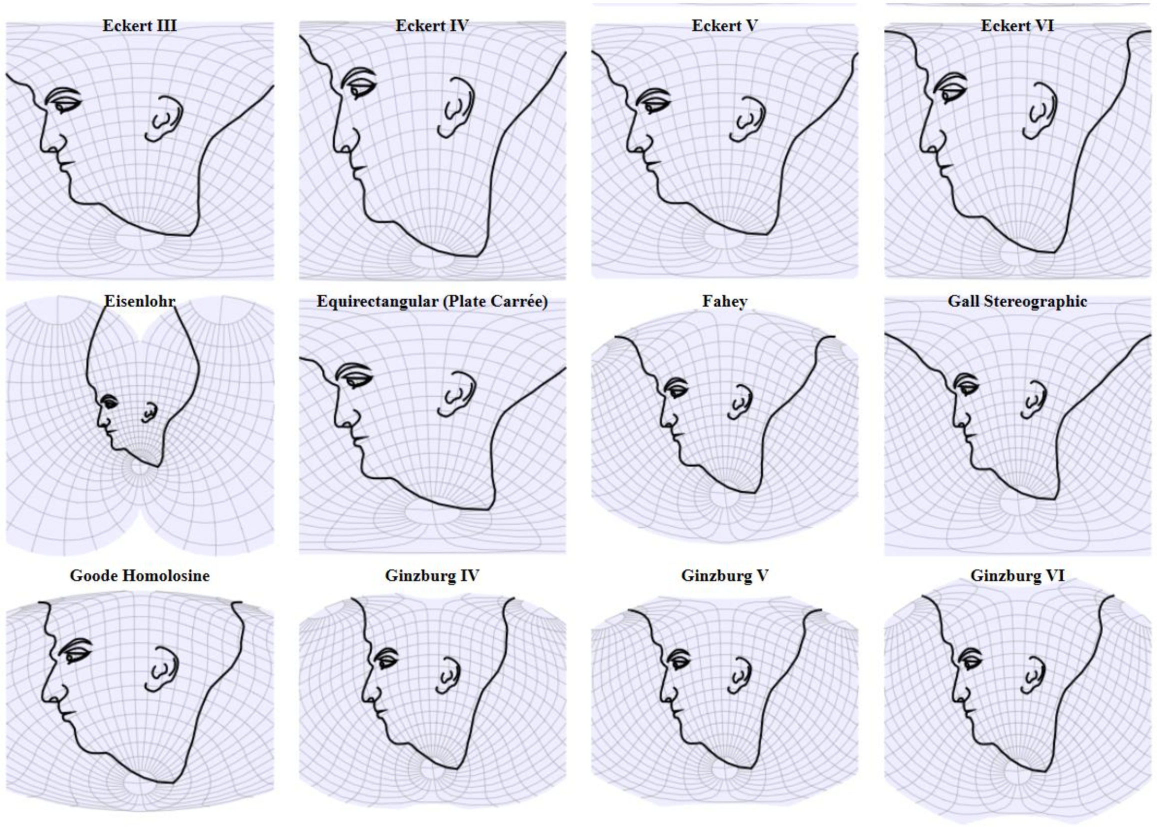


A
Literacy Rates, 2003
(Quartic Authalic)
Percentage of Adults Who are Literate
No Data
17.6 to 53.0
53.1 to 70.6
70.7 to 85.1
85.2 to 94.1
94.2 to 100
B
Literacy Rates, 2003
(Eckert IV)
Percentage of Adults Who are Literate
No Data
17.6 to 53.0
53.1 to 70.6
70.7 to 85.1
85.2 to 94.1
94.2 to 100

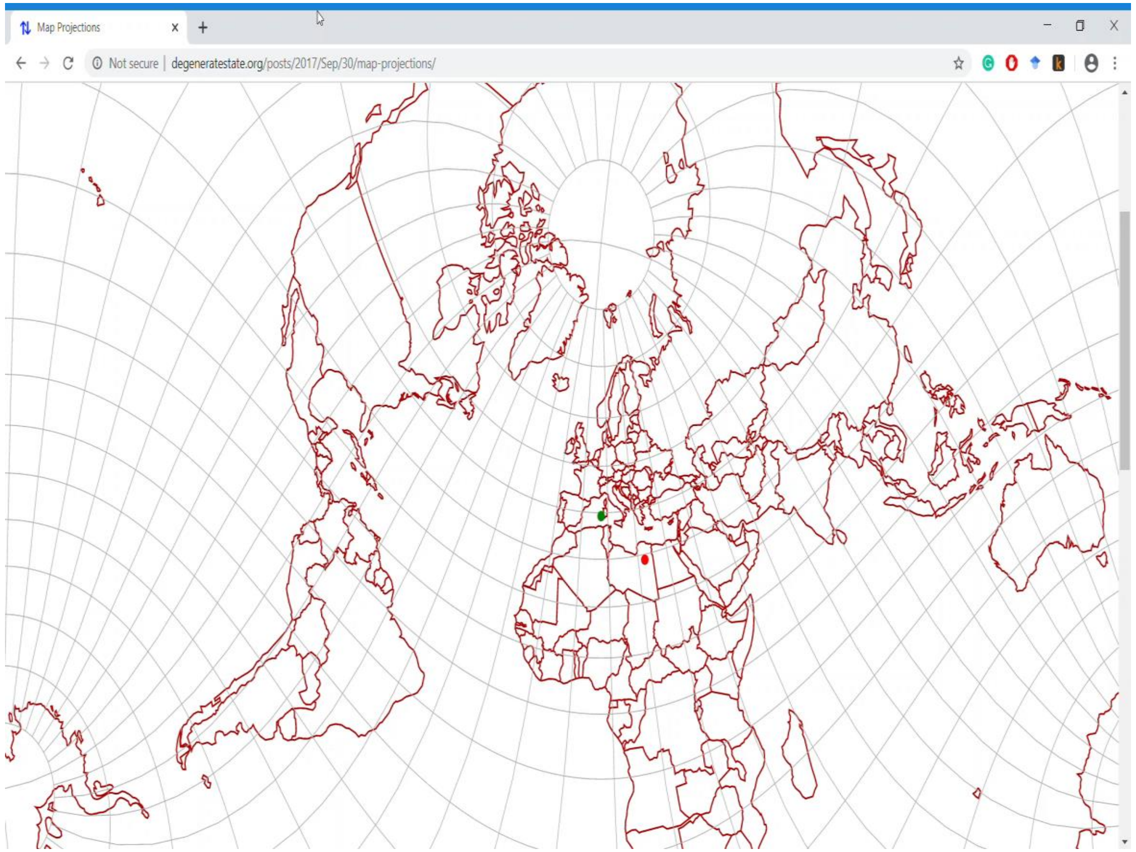
Which Map Projection to Select?

Projection Face – an illustration of the distortions created by different map projections

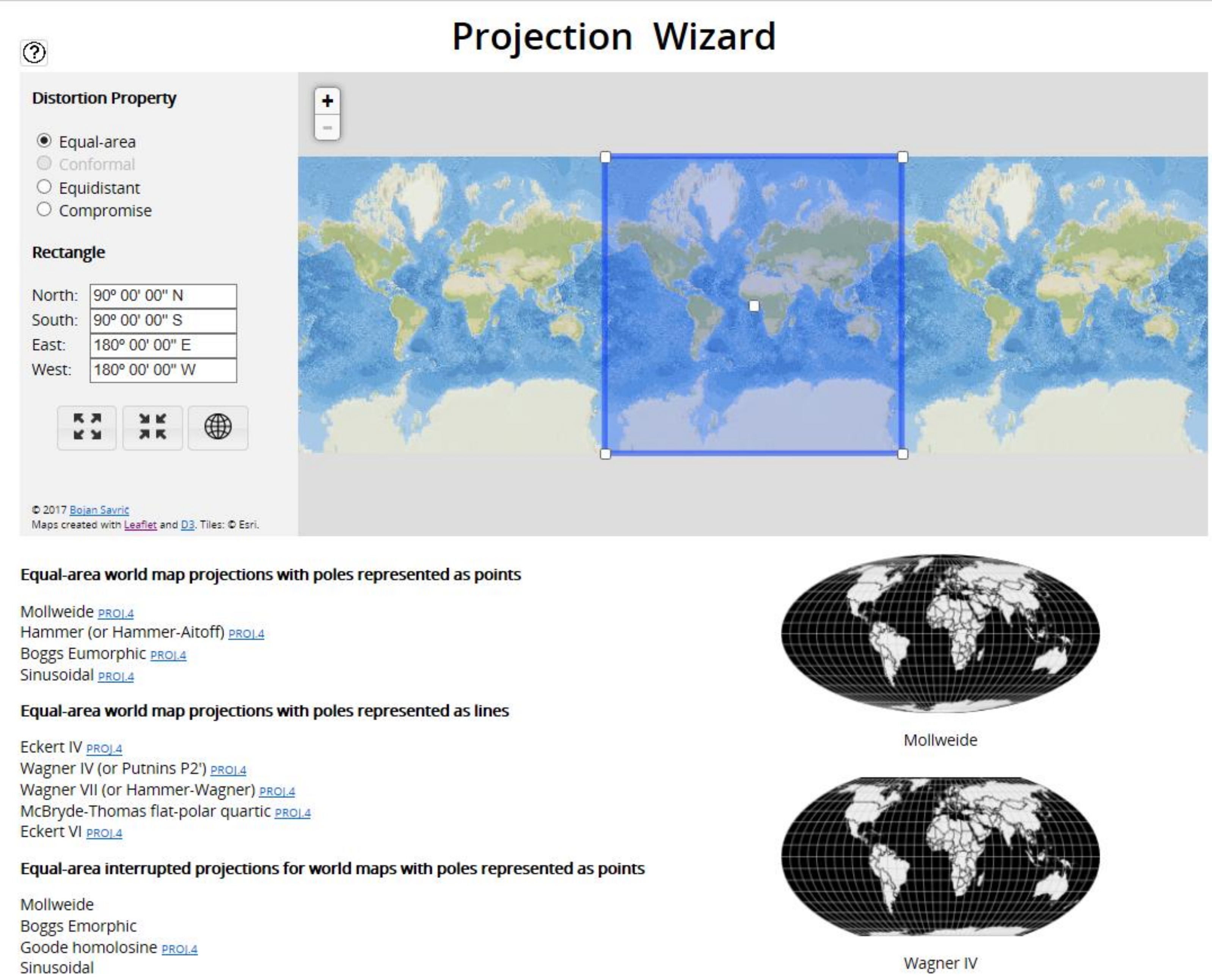




Degenerate State's Map Projections



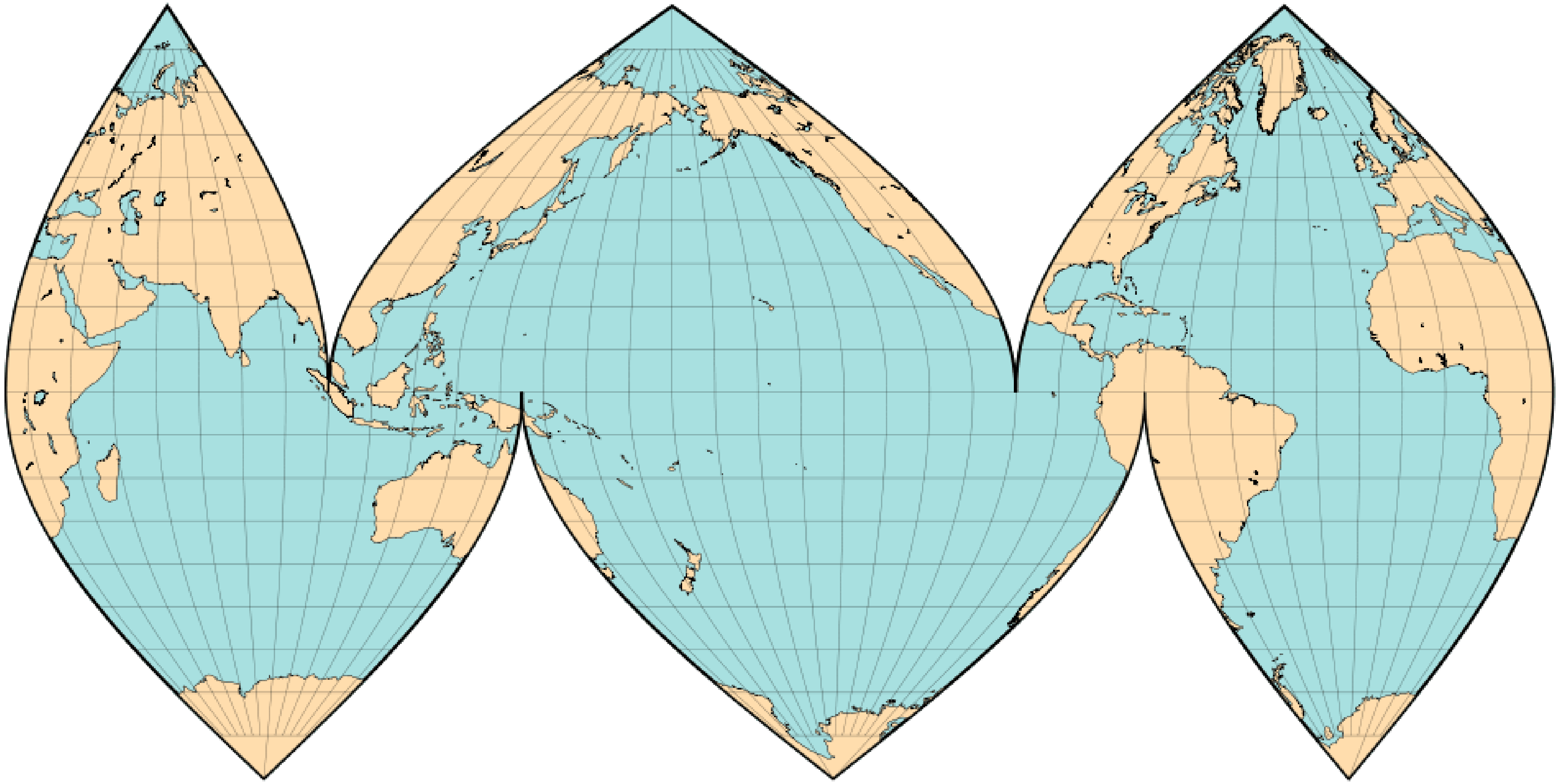
Projection Wizard



The True Size

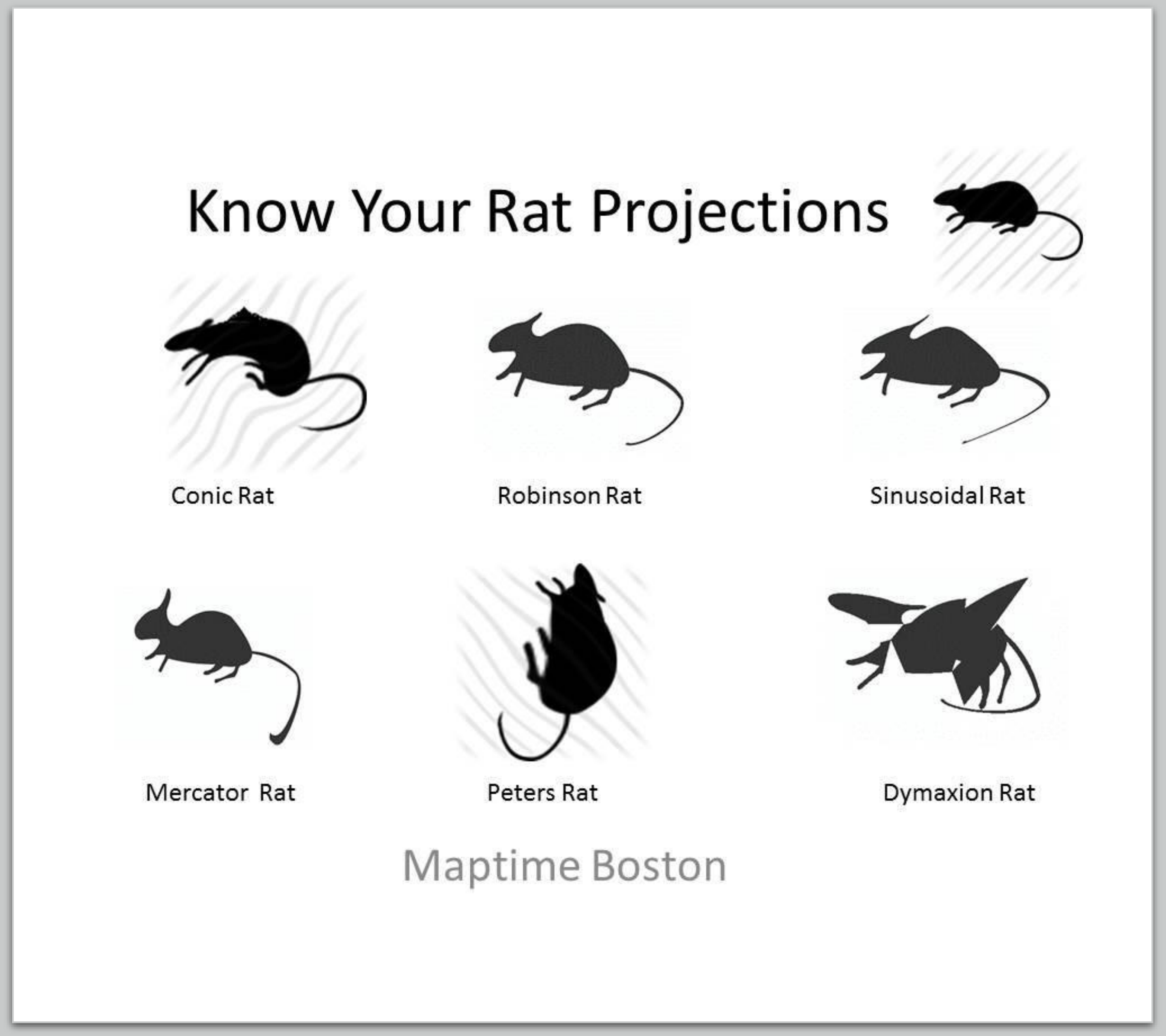
Interrupted Projections

Balance distortions by splitting the surface.



http://www.progonos.com/furuti/MapProj/Normal/ProjInt/projInt.html

Know Your Rat Projections

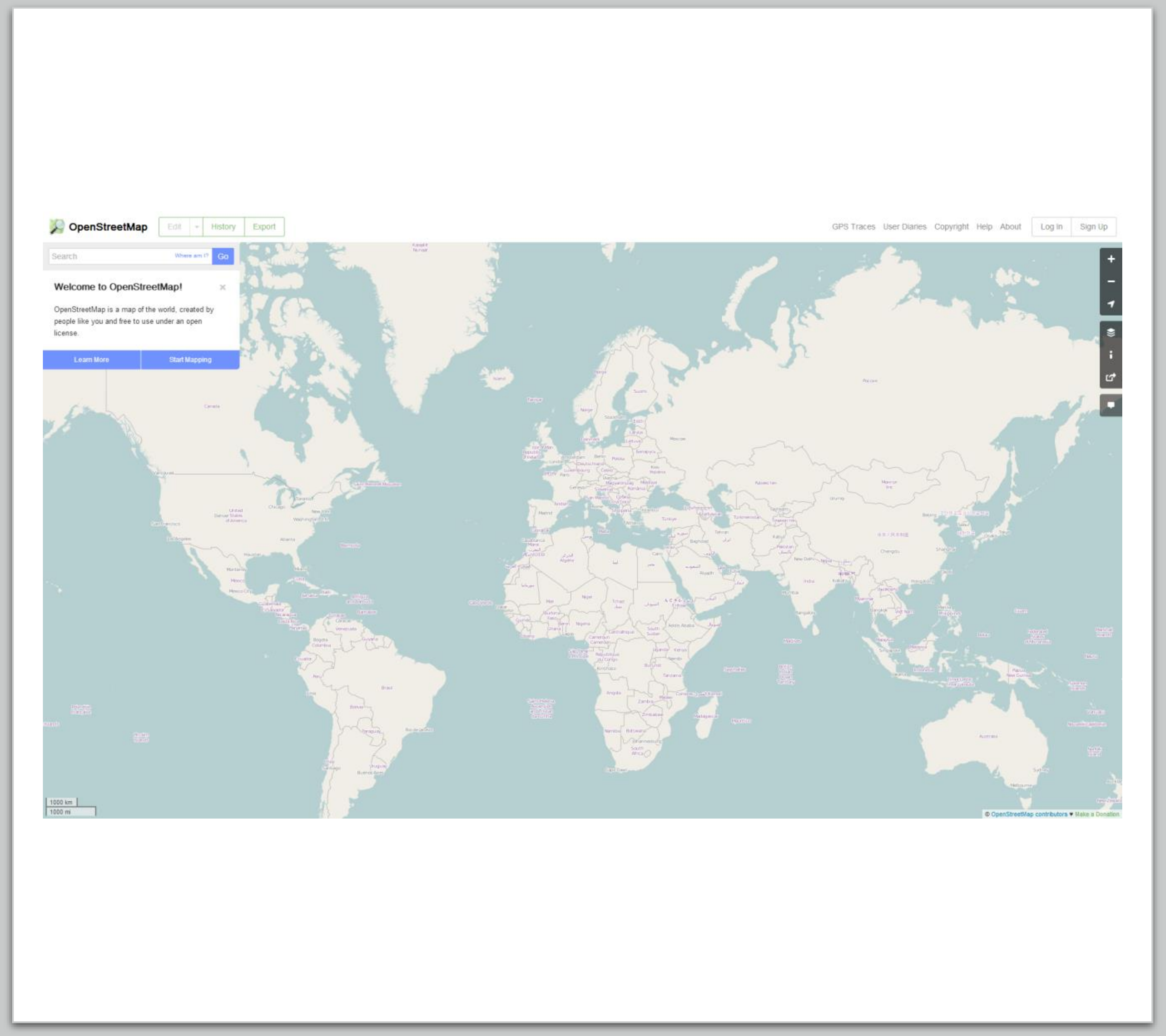


Consider the Following

- The Mercator projection vastly distorts area, but is the basis for the ‘Web Mercator’ used by online systems.

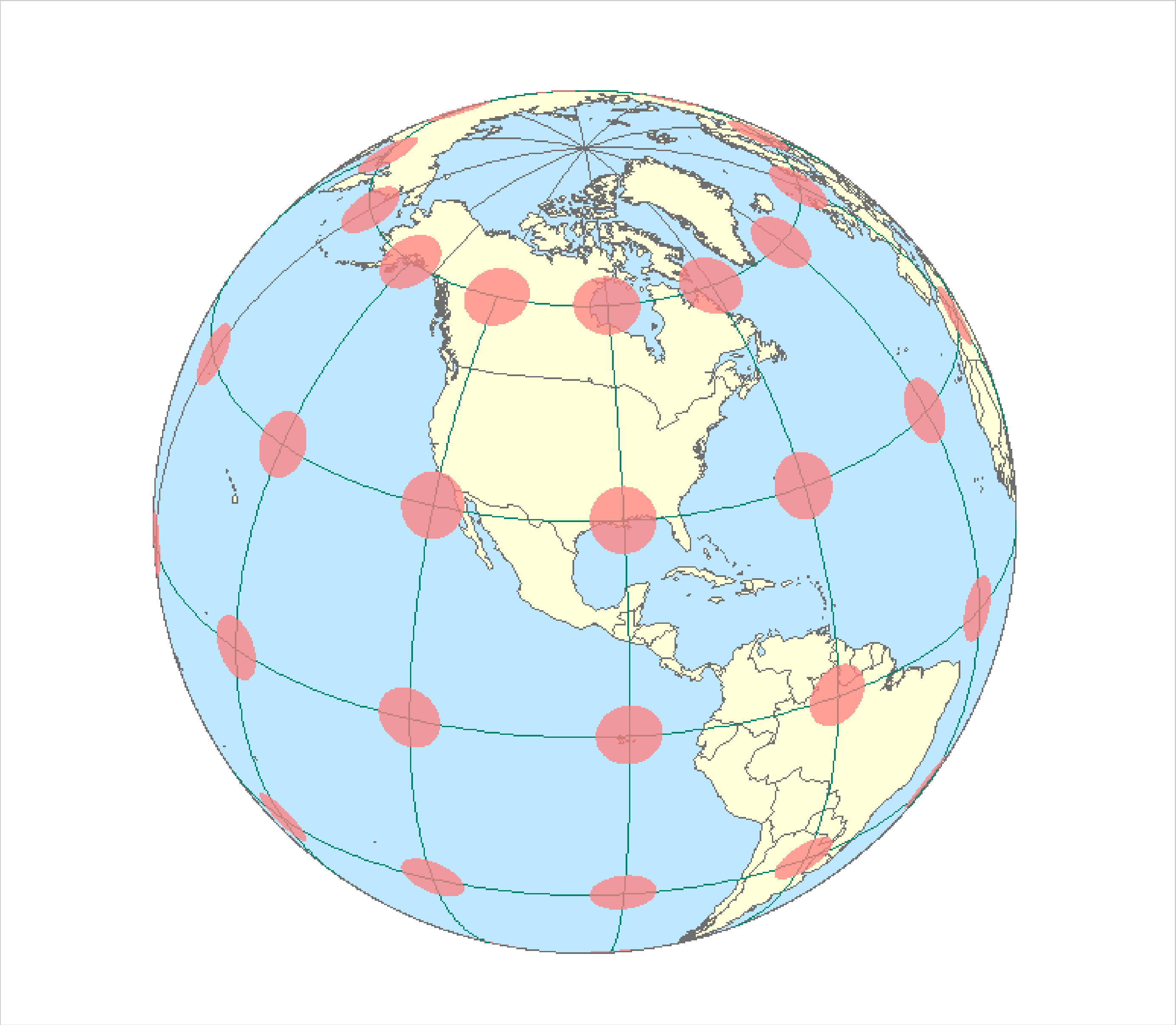
- Answer: Why is Mercator the basis for online mapping?

Open Street Map Program



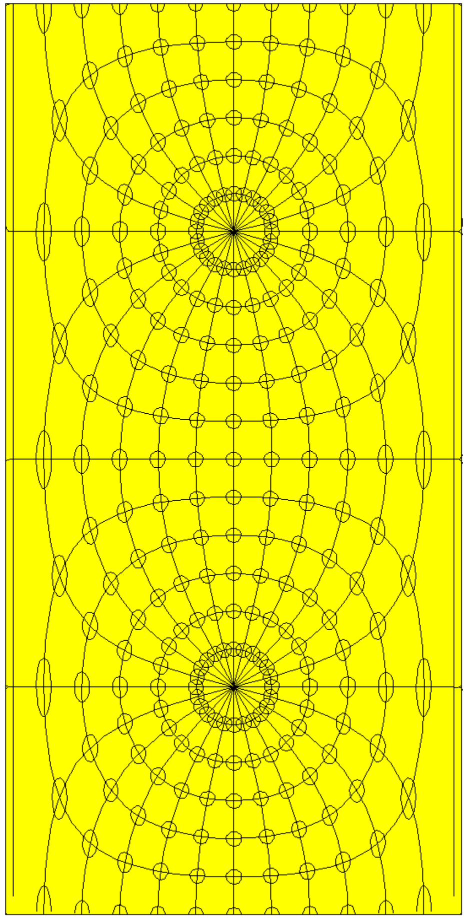
Orthographic Projection

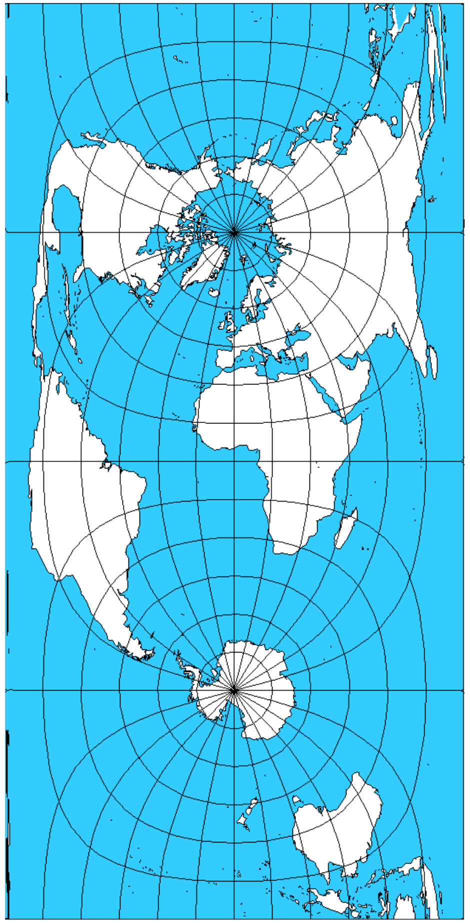
- *Note that on a globe all Tissot Ellipses are the same size and are circular since on a globe both area and shape are preserved correctly*



Identifying Distortion Using Tissot's Indicatrix

- Cassini Projection





Source: Thomas Rabenhorst